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INVERTED SIPHONS FOR OIL TRAPPING

Robert C. Ziegler, et al

Calspan Corporation

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16. ABSTRACT

This report describes investigations of the oil trapping characteristics of inverted siphons as part of a demonstration program for preventing and eliminating oil pollution of the Buffalo River. The program, Project 11020 DJG, was carried out under Grant No. WPRD 263-01-68 from the Environmental Protection Agency to the City of Buffalo, New York. An extensive study was made of the quantity and types of oil that accumulated in an inverted siphon located in the Buffalo sewer system at Memorial Drive and Gibson Street. Oil detectors developed under the program and their use for both automatic and manual measurement of accumulated oil depths are described. A telemetering system permitted oil data to be transmitted to a remote monitoring station located several miles from the siphon. The report discusses in detail the spectroscopic and chromatographic analyses of samples to characterize the nature of the trapped oils. Most of the trapped oil was of petroleum origin and was traced to spills of fuel oil at a nearby railroad terminal. The sampling program demonstrated that inverted siphons are nearly 100 percent effective for trapping surface oils and that the trapping efficiency for emulsified oil carried in the bulk water is extremely low. Described also are the results of tests made with 1/24 and 1/12 scale models of the Memorial Drive siphon based on both Froude and Reynolds scaling criteria.

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ABSTRACT

This report describes investigations of the oil trapping characteristics of inverted siphons conducted as part of a demonstration program for preventing and eliminating oil pollution of the Buffalo River. The program, Project 11020 DJG, was carried out under Grant No. WPRD 263-01-68 from the Environmental Protection Agency to the City of Buffalo, New York. An extensive study was made of the quantity and types of oil that accumulated in an inverted siphon located in the Buffalo sewer system at Memorial Drive and Gibson Street. Oil detectors developed under the program and their use for both automatic and manual measurement of accumulated oil depths are described. A telemetering system permitted oil data to be transmitted to a remote monitoring station located several miles from the siphon. The report discusses in detail the spectroscopic and chromatographic analyses of samples to characterize the nature of the trapped oils. Most of the trapped oil was of petroleum origin and was traced to spills of fuel oil at a nearby railroad terminal. The sampling program demonstrated that inverted siphons are nearly 100 percent effective for trapping surface oils and that the trapping efficiency for emulsified oil carried in the bulk water is extremely low. Described also are the results of tests made with 1/24 and 1/12 scale models of the Memorial Drive siphon based on both Froude and Reynolds scaling criteria.

This report was submitted in fulfillment of Program Number 11020 DJG, Grant Number WPRD 263-01-68 by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.) under the partial sponsorship of the U.S. Environmental Protection Agency.

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CONCLUSIONS

On the basis of the investigations of the oil trapping characteristics of inverted siphon configurations, conducted as part of the Buffalo River Project (Project 11020 DJG), the following conclusions are drawn:

1) As demonstrated by analysis of samples taken from a full-scale inverted siphon located in the sanitary sewer system in Buffalo, New York, and by tests conducted on 1/24 and 1/12 scale models of this inverted siphon, the inverted siphon sanitary sewer design is nearly 100% effective for trapping surface oils. These oils include those that are constantly discharged into the sanitary sewer, such as cooking oils and greases, and petroleum oils that enter into the sewer as a result of accidental or deliberate discharges from gas stations, railroad refueling operations, and other industrial sources.

2) The inverted siphon sewer configuration has nearly zero efficiency for trapping emulsified oils carried in the bulk waters of the sewer.

3) The oils trapped in the particular inverted siphon investigated during this program were of about 30% biological origin and 70% petroleum origin. Specifically, the petroleum-based fuels were diagnosed as being essentially identical to No. 2 fuel oil on the basis of identical infrared spectra and gas chromatograms. No. 2 fuel oil was routinely used in railroad refueling operations in a major terminal adjacent to the inverted siphon section under study. Such oils were found, by separate sample collection, to be entering the Buffalo Sewer line from an oil sump overflow in the railroad terminal.

4) Most of the oil that accumulated in the vertical chambers of the inverted siphon must have entered the siphon section as floating oils in large spills in order to be consistent with the efficiency of the collection process, as noted above, and with the gas chromatographic analyses of the accumulated manhole contents.

5) It is practical to install oil detectors permanently in the vertical chambers of the inner manholes of an inverted siphon to monitor depths of accumulated oil and to telemeter the data to a remote location via a radio frequency link. It was demonstrated that the oil detection sensors developed under this program are sufficiently rugged to withstand prolonged exposure to the sewer environment.

6) As determined by the limited number of tests performed in the laboratory on 1/24 and 1/12 scale models of the real world inverted siphon studied in this program, the oil trapping characteristics of inverted siphons can be reasonably well scaled using the Froude number.

RECOMMENDATIONS

The following recommendations concerning oil trapping in sewers are based on the work performed as part of the Buffalo River Project (11020 DJG).

1) It is recommended that a system of oil detectors and telemetering stations be installed at inverted siphon locations in typical municipal sewer systems in order to permit data on depths of oil accumulated in the vertical chambers of the system to be monitored at a central location. Such a system would allow sources of major oil discharges to be isolated. In addition, provisions to pump out the accumulations of oil on a timely basis would prevent large quantities of oil from reaching the treatment plant.

2) Consideration should be given to the construction of an oil storage facility adjacent to an inverted siphon which is known to accumulate large quantities of oil. Oil detectors located in the inner manholes of the siphon could automatically activate pumps that would transfer the accumulated oil to the storage facility.

3) More extensive investigations should be undertaken to determine the limitations of modeling oil trapping configurations. Specifically, the present modeling investigations should be expanded to include a wide range of flow conditions and other oil types, and to determine the feasibility of separating emulsified oil from the bulk water stream, either by modifying the design of inverted siphons or providing an entirely new design concept. For example, it might be desirable to elongate the inner manhole chambers along the direction of flow to provide a larger oil storage capacity and a longer time for oil in the bulk water to rise in the chamber.

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INTRODUCTION

In May 1968 the City of Buffalo made application to the Federal Water Pollution Control Administration for a Research and Development Grant for preventing and eliminating oil pollution of the Buffalo River under the provisions of the "Clean Water Restoration Act of 1966". On 24 July 1968 the City of Buffalo accepted a Federal Research and Development Grant (Project 11020 DJG) for $552,895.00, or 75% of eligible costs whichever is less. Twenty-five percent of the eligible costs have been provided by the City of Buffalo, the Buffalo Sewer Authority, the County of Erie, and the New York State Health Department in the form of either direct cash contributions or in-kind services. On 18 October 1968 a contract was negotiated with Cornell Aeronautical Laboratory, Inc. (now Calspan Corporation) of Buffalo, New York to provide the research, engineering, and development support required for the program (Calspan Corporation is the new name for Cornell Aeronautical Laboratory. Because this report was completed prior to the date of our name change (November 17, 1972), Cornell Aeronautical Laboratory nomenclature has been retained throughout this report.).

The overall objective of the program was to prevent oil pollution of the Buffalo River. Specific objectives of the program were:

1) to develop, utilize and evaluate equipment and techniques for containing and removing oil in the River, including floating mechanical barriers and pneumatic barriers for preventing the movement of surface oil, oil skimmers, debris booms, and a boat containing oil and debris removal equipment;
2) to develop instrumentation for detecting oil in sewers;
3) to evaluate means for trapping oil in sewers; and
4) to devise methods for sampling oil to determine its concentration on the river, and to develop methods for analyzing the collected samples to determine their sources.

This report describes the evaluation of inverted siphons as a means for trapping oil in sewers. The entire program is described in a summary report (Reference 1). Other specific phases of the program are discussed in three other separate topical reports (References 2-4) covering detection of oil in sewers, the evaluation of a pneumatic barrier for oil containment, and oil sampling and analysis for spills in watercourses.

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BACKGROUND

The deliberate or accidental discharge of oil into sewer systems presents two potential problems. First, excessive quantities of oil can interfere with the sewage treatment process. Even if the quantities are not sufficient to cause interference they will be discharged along with the treated sewage into the receiving waters unless adequate oil removal and storage facilities are available. Second, in many municipalities storm sewers and sanitary sewers are combined. During heavy rains the combined flow in the sewers exceeds the capacity of the treatment plant and the excess flow containing both storm water and sewage is discharged into waterways. In the case of Buffalo, part of the combined flow is discharged into the Buffalo River. Thus oil discharged into the sanitary sewer system is carried into the Buffalo River during storms.

Clearly the most desirable solution to these potential problems is to prevent oil from being discharged into the sewers in the first place. Although regulations are in effect which prohibit the discharge of oil into sewers, strict enforcement of these regulations is difficult and costly. Clandestine discharges, often detected after the fact, are often difficult to associate with the source. A detection system consisting of a network of oil detectors located at selected points in the sewers, could become an important asset to an enforcement program. One phase of the Buffalo River Program involved the development of sensors for detecting oil in sewers. This phase of the program is reported in detail in a separate topical report (Reference 2). While strict enforcement programs can greatly reduce the possibility of oil discharges into sewers, accidental or clandestine discharges will occur from time to time. Therefore, it is desirable to have a means for trapping oil in sewers in order to prevent its flow into the treatment plants or into watercourses during periods of storms. Methods for trapping oil in sewers is the topic of the present report.

Prior to initiation of the Buffalo River Program it was known from experience that oil accumulations occur in the manholes of inverted siphons. Inverted siphons are used in sewer lines when the sewer crosses another sewer, a watermain, or a gas line at the same elevation. The sewer line is dropped below its normal level for a distance sufficient to clear the interfering line. Figure 1 is a diagram of an inverted siphon installation located in the Buffalo sewer system at Memorial Drive and Gibson Street. In this case the inverted siphon was necessary to cross a storm sewer located at the same depth. Periodically it is necessary to pump out the large quantities of oil which accumulate in manholes No. 2 and No. 3. Oil accumulations corresponding to oil depths greater than ten feet have been observed in manhole No. 2. This corresponds to more than 900 gallons of oil.

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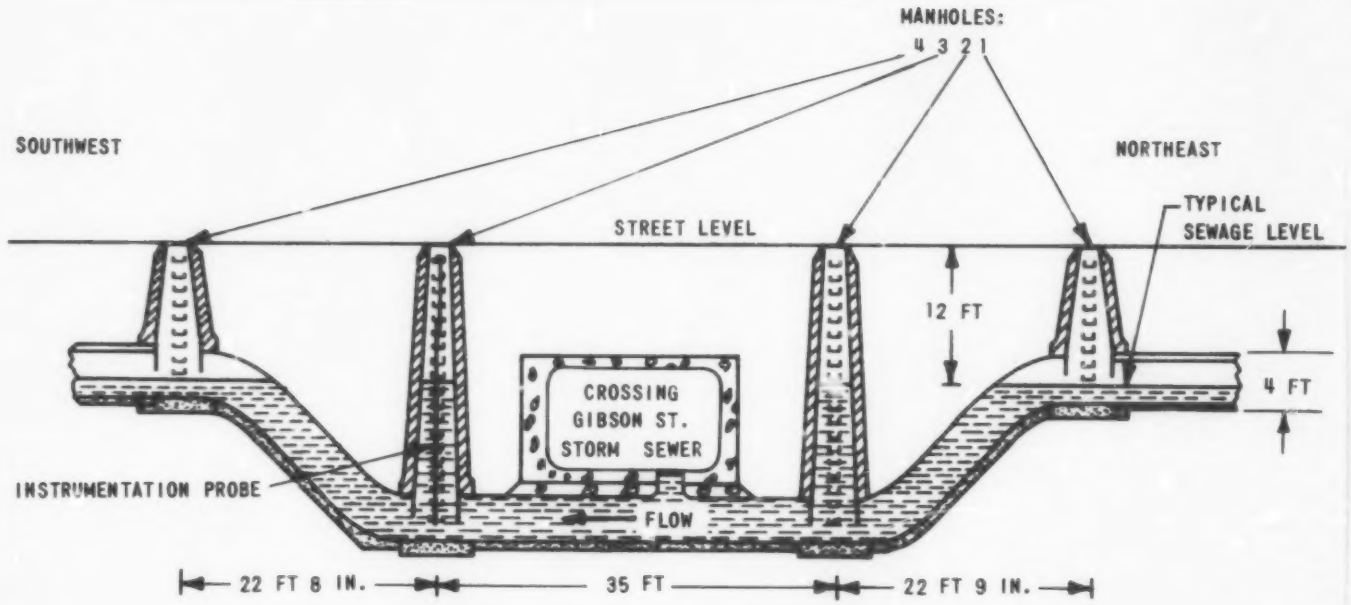

Figure 1 CROSS SECTION OF MEMORIAL DRIVE INVERTED SIPHON

The present program involved an extensive study of the oil trapping efficiency of the particular inverted siphon configuration shown in Figure 1. This effort included monitoring of the oil accumulations in manholes No. 2 and 3 using oil detection sensors developed on another phase of this program, the collection and analysis of samples both upstream and downstream of the inverted siphon as well as in the inner manholes, and laboratory tests involving 1/12 and 1/24 scale models of this siphon.

The following sections describe specific aspects of the inverted siphon evaluation.

MONITORING OF OIL ACCUMULATION IN THE SIPHON

Under the Buffalo River Program three different types of sensors for detecting oil in sewers were developed. One sensor is based on the difference in the electrical conductivity of oil and water. Another is based on differences in thermal conductivity. The last is based on spectral transmittance differences between oil and water. The three sensor types are described in detail in a separate topical report entitled "Detection of Oil in Sewers" (Reference 2). However, a brief discussion of the first two types is in order since they are most suited for monitoring oil thicknesses in excess of 1/4" and were most suitable for use in the inverted siphon.

The electrical conductivity probe consists of a coil wound with stainless steel wire and energized with an alternating current at a frequency of about 10 megahertz. When the coil is surrounded by a conductive fluid part of the generated power is absorbed by the fluid. The amount of power absorbed, which is measurable, depends on the conductivity of the fluid. This device easily indicated conductivity of water for dissolved ion solute concentrations of some five parts per million and higher. Concentrations lower than five parts per million are almost never found in water that has not recently been distilled. Thus, the device can easily distinguish between oil and water in sewers. Oils which accumulated in the manholes in the inverted siphon were easily detected by this RF oscillator probe.

The thermal conductivity probe employs a self-heated thermistor, whose resistance indicates its temperature, to distinguish sewer fluids in which it is immersed on the basis of the heat-exchange characteristics. Basically the unit contains one thermistor, one small incandescent lightbulb, a rheostat, an indicating meter, and a battery. The thermal probe easily distinguishes between normal sewage and oil.

Two sensors (one of the electrical conductivity type and the other of the thermal conductivity type) were incorporated into a single battery-operated portable probe as shown in Figure 2. The stainless steel wire coil for the electrical conductivity sensor is at the left in the figure. The right end of the probe contains the self-heated thermistor within the hollow tube. The case shown contains the meters, circuitry, and batteries. The electrical cable is marked at one-foot intervals to permit the depth of the sensor from the top of the manhole to be determined. This ruggedized probe was evaluated by personnel of the Buffalo Sewer Authority and Cornell Aeronautical Laboratory and found to be a convenient and effective means for determining the level and thickness of oil collected in manholes. In fact, the probe has been used by the Buffalo Sewer Authority to collect oil-accumulation data.

In order to evaluate the suitability of the electrical conductivity sensor and the thermal conductivity sensor to withstand the sewer

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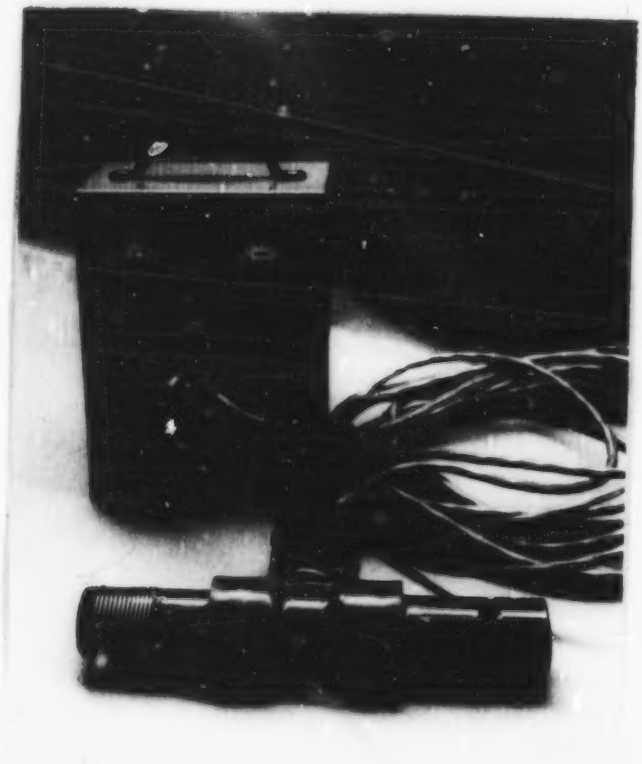


Figure 2 PORTABLE PROBE

environment on a long term basis an experimental instrumentation probe was built and installed in manhole No. 3 of the inverted siphon. This probe consisted of a total of 13 sensors, six of the electrical conductivity type and seven of the thermal type, spaced alternately at one-foot intervals along the length of 18 feet of polyvinyl chloride tubing. The tubing was positioned so the uppermost sensor was approximately six inches above the usual level of sewage in the manhole. The bottom sensor was approximately flush with the bottom of the manhole sheath extending into the siphon as shown in Figure 3. Oil depth measurements were made by removing the manhole cover and attaching the probe cable to a portable readout device.

Following the initial evaluation of the fixed instrumentation probe a more permanent installation was fabricated which permitted the oil depth measurement to be made automatically at selected intervals and telemetered from the site to a receiver and recording station located at Cornell Aeronautical Laboratory, a distance of several miles away. The new probe consisted of eight radio frequency electrical conductivity probes spaced at one-foot intervals along a 34 millimeter diameter polyvinyl chloride pipe ten feet in length. The upper end of the pipe was attached to a polyurethane foam float enclosed in an aluminum housing for impact protection. The completed probe is shown in Figure 4 before installation in the siphon. The flotation device allows the entire probe to be floated vertically in the manhole. Oil depths up to eight feet could be measured with this unit.

The various oil detectors that were developed during this program and installed for evaluation provided a large quantity of data on the oil trapping characteristics of inverted siphons as exemplified by the specific inverted siphon located on Memorial Drive at Gibson Street in the Buffalo Sewer System. The acquired data indicate that within a period of a few days hundreds of gallons of oil can accumulate in the inner manholes of the siphon. Unusually large quantities of oil were accumulated in the siphon during March and April of 1969. Most of these accumulations were attributed to diesel fuel oil spilled during refueling operations at a nearby railroad terminal. Plots of the depths of oil in manholes No. 2 and No. 3 are shown in Figures 5 and 6 respectively for the period of mid-March to mid-May 1969. These plots indicate the measured depth of oil in the siphon on the dates the measurements were taken. The maximum depth of oil possible in manholes 2 and 3 is approximately 14 1/2 feet. This depth can occur only when the main sewer pipe entering the siphon is filled, at which time the level in the inner manholes rises to the level of the top of the input pipe or somewhat higher because the specific gravity of the trapped oil is less than that of water. Rather abrupt fluctuations in the oil level in the inner manholes are indicated in Figures 5 and 6. The inner manholes of the siphon were pumped out on March 14, April 9, April 24 and May 9, 1969. The decreases in oil depth following pump out of the siphon are evident in the figures with two minor exceptions. The indicated measurements were not made immediately following pump out, therefore some

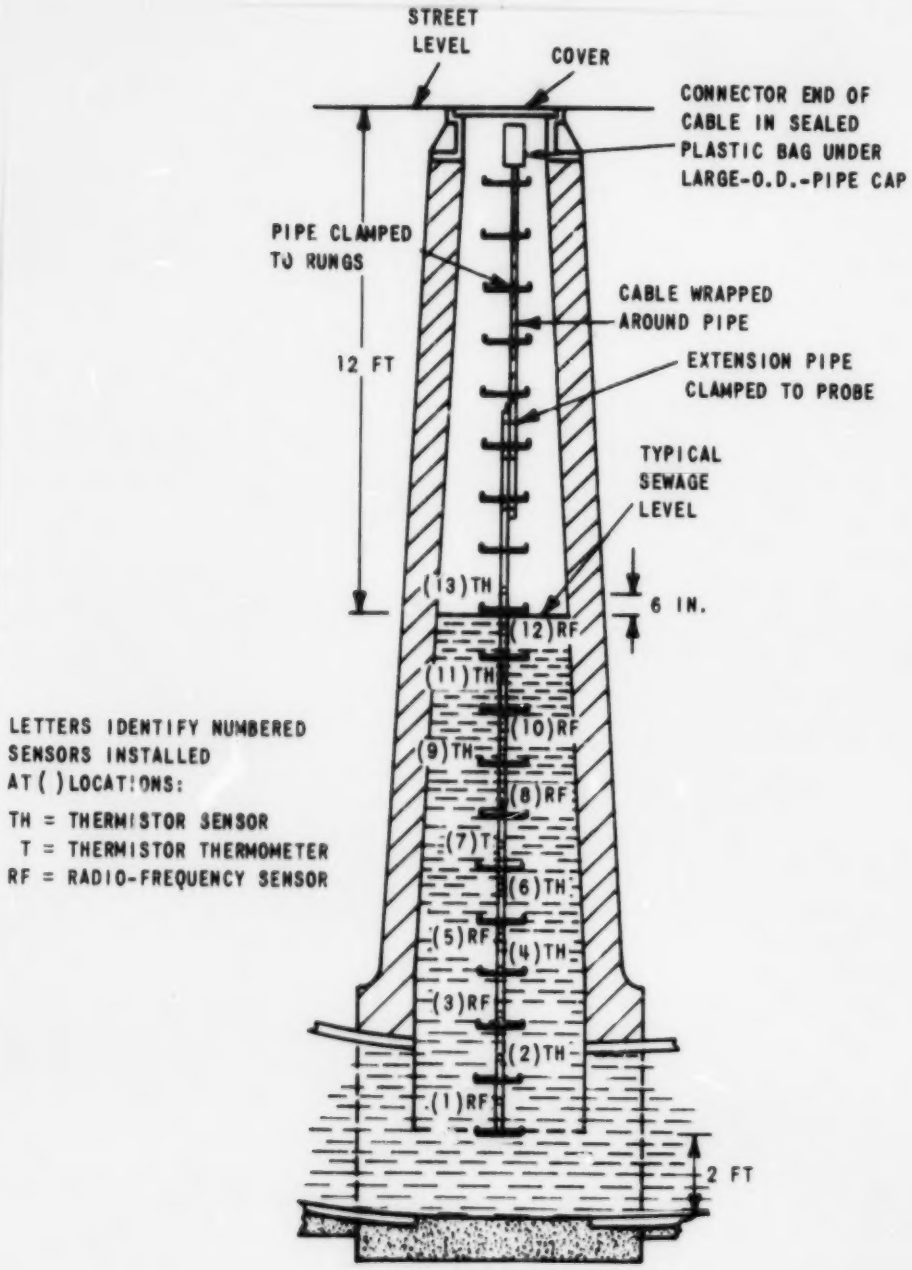


Figure 3 **CROSS SECTION OF MANHOLE 3 OF MEMORIAL DRIVE INVERTED SIPHON SHOWING INSTALLATION OF INSTRUMENTATION PROBE**

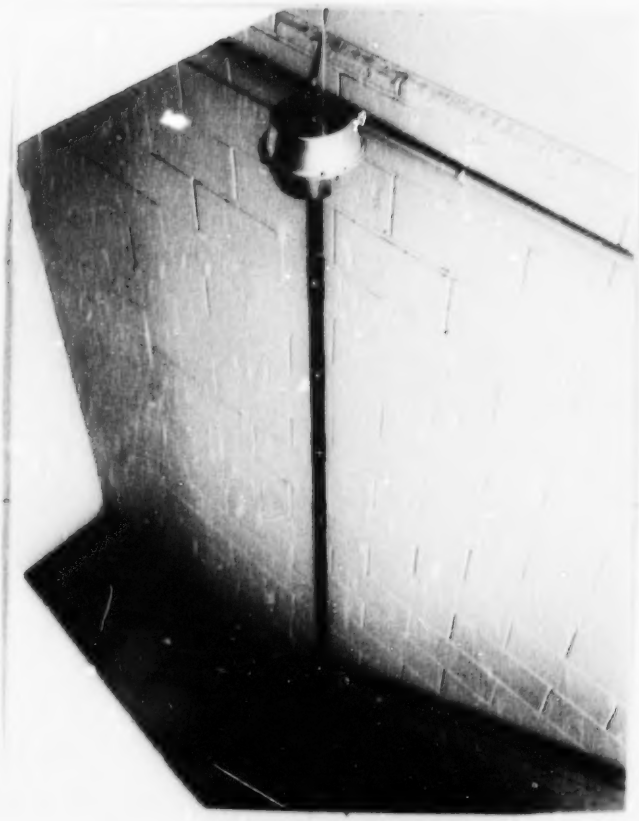


Figure 4 POLYVINYL CHLORIDE SPAR BUOY SENSOR

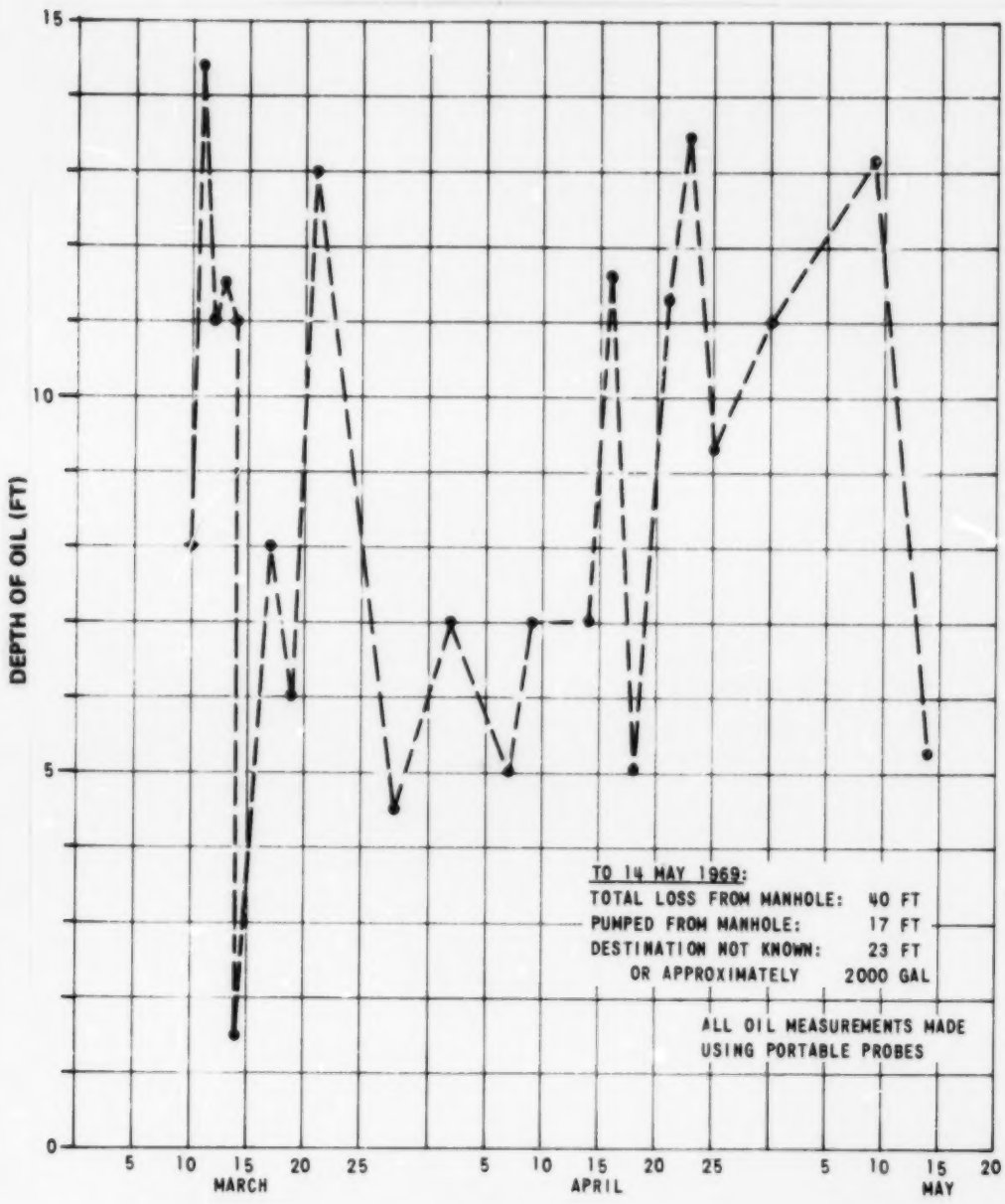


Figure 5 OIL ACCUMULATION MEASURED IN MANHOLE 2 OF MEMORIAL DRIVE INVERTED SIPHON (1969)

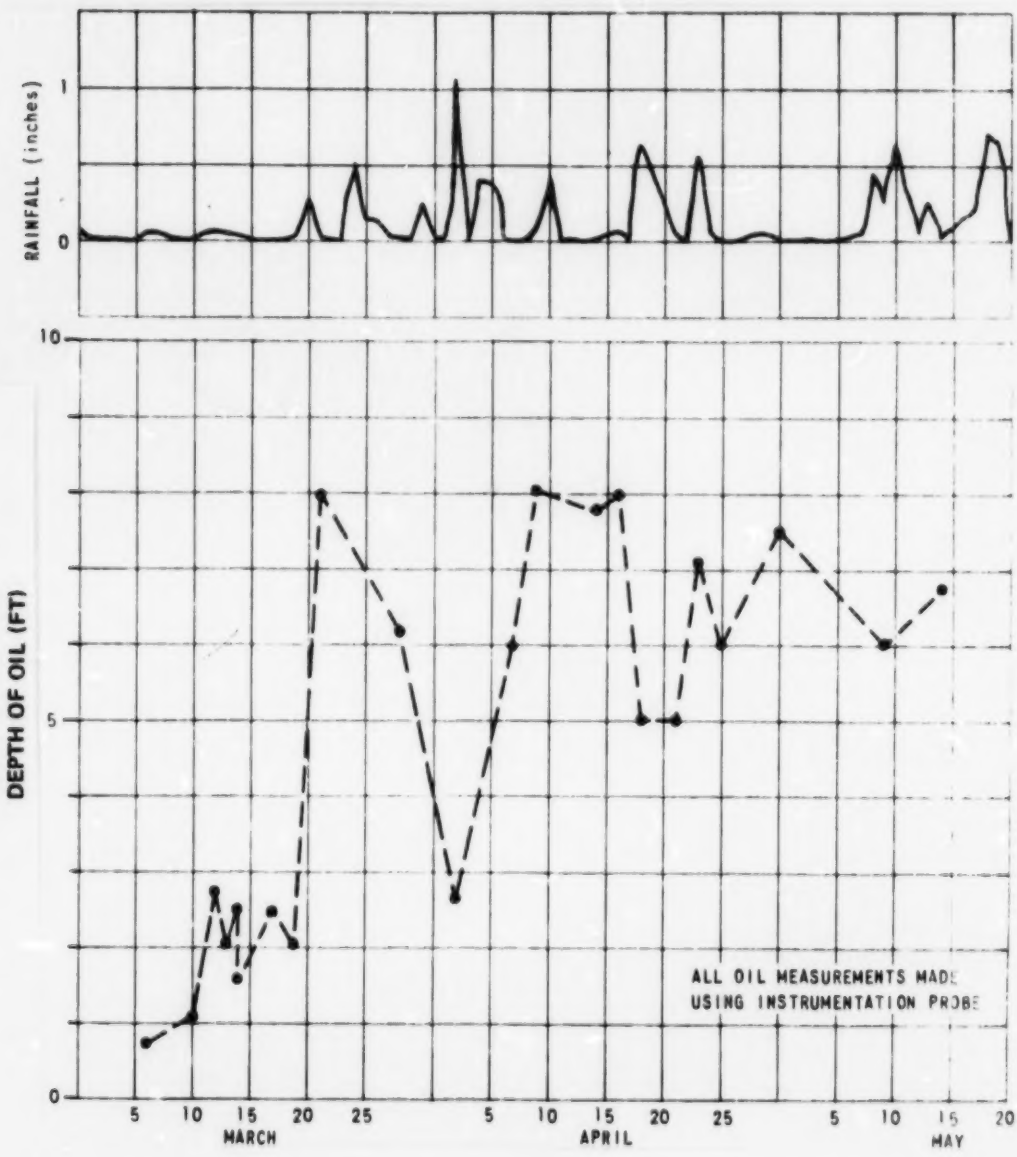


Figure 6

SIMULTANEOUS PLOTS OF RAINFALL AND OF OIL ACCUMULATION MEASURED IN MANHOLE 3 OF MEMORIAL DRIVE INVERTED SIPHON (1969)

accumulation of oil may have occurred between pump out and the date of measurement. Thus, in Figure 5 the reading on 14 April shows no change from the previous reading made prior to pump out. In Figure 6 the reading taken at 14 May shows a greater depth of oil than the reading taken prior to pump out of the siphon. The total loss of oil from the siphon cannot be accounted for solely on the basis of the oil pumped out. For example, a substantial decrease in the depths of oil in manhole No. 2 is observed for the period from 21 March to 28 March even though no oil was pumped from this manhole in that period. For the period indicated (10 March to 14 May), the total oil lost from manhole No. 2 was 40 feet or about 3500 gallons. Only 17 feet of this can be accounted for by pumping. This leaves 23 feet or approximately 2000 gallons of oil unaccounted for.

A plot of daily Buffalo rainfall over the three-month measurement period, based upon U. S. Weather Bureau records, is shown at the top of Figure 6. These data suggest that some oil loss from the siphon may be attributable to washing out of the siphon by the heavy run off accompanying periods of high precipitation. The correlation coefficient for losses caused by rainfall has been calculated to be approximately 0.25 for the measurement interval shown.

The total amounts of oil trapped in manholes 2 and 3 in March 1969 are shown in Figures 7 and 8 respectively. The upper curves indicate the total amount of oil trapped (projected quantity) including the oil pumped from the siphon. The lower curves indicate the actual oil depth at the time the measurements were made. Figure 7 indicates that from the period of March 6 to March 21 over 1300 gallons of oil were trapped by manhole No. 2. Figure 8 indicates that during the same period manhole No. 3 trapped more than 750 gallons of oil. Thus, in a 15 day period more than 2000 gallons of oil were trapped in this inverted siphon. The large quantities of oil trapped during this period are attributed primarily to the spillage of diesel fuel oil at a nearby railroad terminal during refueling operations. The monitoring activity at this particular inverted siphon and the associated large quantities of oil that were detected received considerable publicity in one of the local newspapers. As a result of a State directive the railroad installed concrete refueling pads and a collection basin to prevent spilled oil from entering the Buffalo Sewer System.

The above example illustrates the profound importance of a regular monitoring program for enforcing pollution laws.

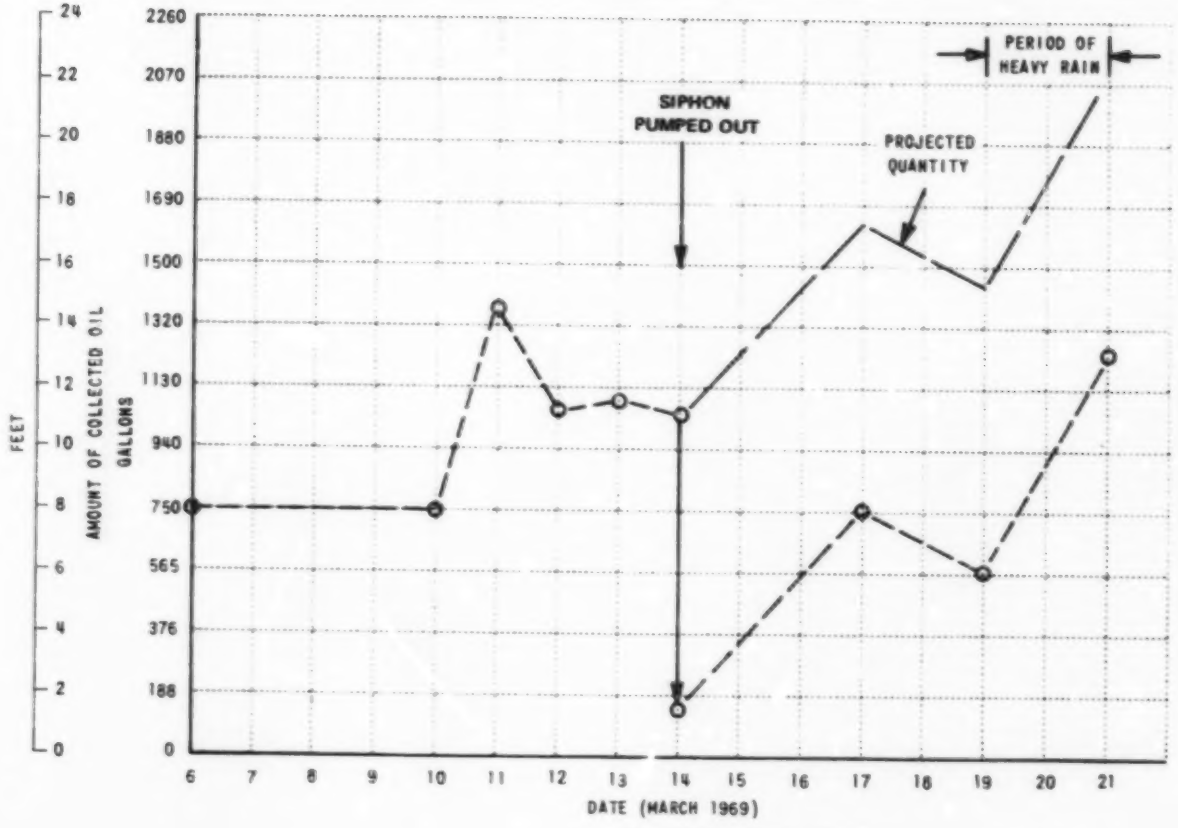


Figure 7 OIL ACCUMULATION MEASURED USING PORTABLE PROBES IN MANHOLE 2 OF MEMORIAL DRIVE INVERTED SIPHON

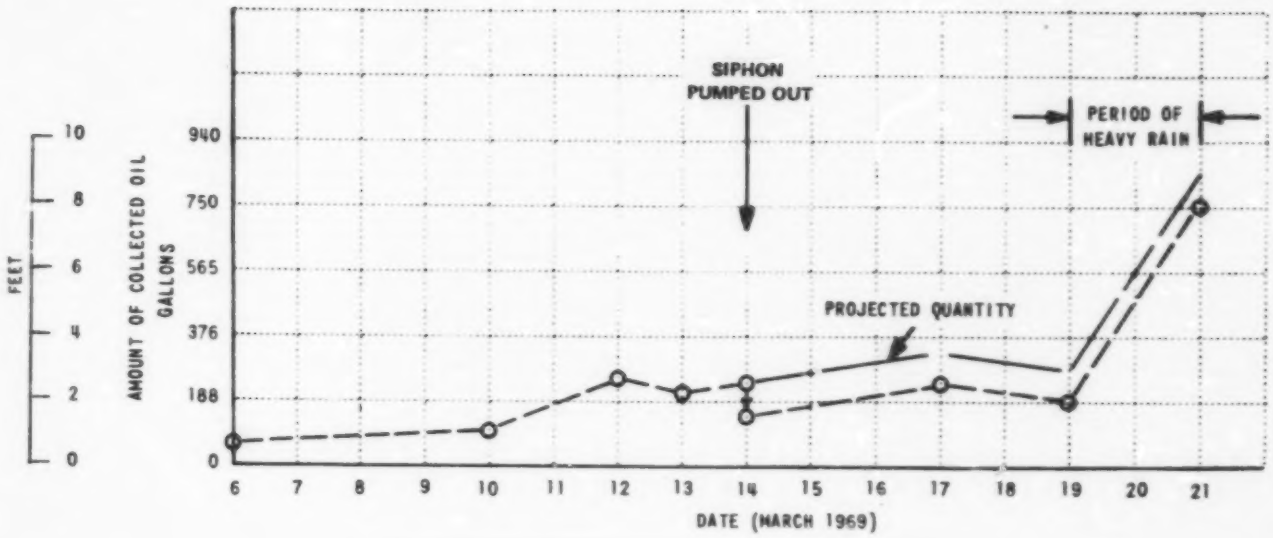


Figure 8 OIL ACCUMULATION MEASURED USING PORTABLE PROBES IN MANHOLE 3 OF MEMORIAL DRIVE INVERTED SIPHON

SAMPLE COLLECTION AND ANALYSIS

The previously described monitoring studies, based on oil depth measurements only in the inner section of the inverted siphon, provided useful information on the general trapping characteristics of this type of configuration. However, the evaluation of the overall effectiveness of an inverted siphon for trapping oil requires information on the amount of oil entering and exiting the siphon as well as on the amount of oil actually collected in the inner manholes. The evaluation should also include identification of the types of oily material normally flowing in the sewer at the siphon location. A carefully planned sampling program was initiated in order to obtain the required information. The sampling program was accompanied by an intensive laboratory study of the characteristics of the samples obtained.

EVALUATION OF TRAPPING EFFICIENCY OF THE INVERTED SIPHON

The sampling program to evaluate the efficiency of the inverted siphon for trapping bulk oil suspended in the water volume was begun in 1969 and completed during 1970. The results of the monitoring phase of the program discussed previously, indicated that large amounts of oils periodically accumulated in the two innermost manholes of the siphon. For enforcement purposes, it is important to know the origin of these very large amounts of oil and whether or not they could be derived from oil emulsified in the bulk. As noted previously, the source of much of this oil had been traced earlier by the Buffalo Sewer Authority and the New York State Environmental Conservation Department to a railroad refueling installation nearby. This identification by source was confirmed by analyses conducted by Cornell Aeronautical Laboratory in the course of the Buffalo River Program.

During 1969, one extensive sampling period extended over a full week, night and day. Continuous results were obtained over the final five days of this seven-day period wherein the influent and effluent streams were sampled every 30 minutes at manholes No. 1 and No. 4 (see Figure 1), respectively. These samples were composited daily and analyzed for the total concentration of hexane-extractable materials and for the relative proportions of oils of biological and of petroleum origin. In addition, the central manholes, Nos. 2 and 3, were sampled every day and at the beginning and the end of the program. The samples from the two inner manholes were taken at two-foot depth intervals starting at the top of the oil column and analyzed for total hexane-extractable materials only. The purpose of the latter sampling was to attempt to relate the inflow content and the outflow content to the change of net storage in the inverted siphon.

Prior to initiation of the sampling program, the accumulation of oils and solid burden in the siphon manholes was completely removed. The flow volume through the inverted siphon section was calculated by means

of the Manning equation which relates flow volume to the hydraulic properties of the channel. The required data on flow depths in the inlet and outlet sections were recorded by a staff gauge.

The results of the analysis of the inflow-outflow samples are presented in Table 1 which lists the total extractable material in samples collected upstream of the inverted siphon and the total extractable material in the samples collected downstream of the inverted siphon at manhole No. 4. These total extractables are further subdivided according to percent fatty matter and percent hydrocarbons. During the entire course of this round-the-clock survey, the concentration of hexane-extractables in the influent stream averaged about 23 parts per million. This is a value typical of the concentrations received routinely at the City of Buffalo Sewage Treatment Plant from all of the combined sewage influents. Approximately 80% of the extractable oily content of the influent stream was material of biological origin. It is apparant that the bulk waters flowing through the sewers do not carry enough oil to account for the gross accumulations noted in the inverted siphon section, and therefore, more attention must be given to potential surface spills from industrial sources.

The overall results presented in Table 1 indicate a negative trapping efficiency for oil in the bulk water. However samples collected from manholes No. 2 and No. 3 during the test period indicated a significant increase in storage. Dry weather flow conditions occurred during the sampling period with the exception of one short period when a high intensity storm recorded approximately 0.75 inch of rainfall at the Buffalo Airport Station. The effects of the storm were noted in the gauging data for approximately two hours, with peak flows reaching 20 MGD, compared to an average of 1.65 MGD for the entire sampling period and a dry weather flow average of 1.43 MGD. Omitting the data included in the period of heavy rainfall and reevaluating the inflow-outflow data, indicates that, at best, the inverted siphon trapped 20% of the potential emulsified oily pollutants entering in the bulk water.

Figure 9 shows the infrared spectra of the chloroform extractable matter (chloroform extraction has been found to be more complete than hexane extraction) in the bulk water entering and exiting the inverted siphon section of the sanitary sewer. Casual inspection of these two spectra shows that they are essentially identical and that transit of the bulk water through the inverted siphon did not modify either their properties or their content in any significant way.

During the 1969 sampling season an investigation was also made of the effects of the inverted siphon on pollutants carried on the surface of the water. Surface samples upstream and downstream of the inverted siphon section and in the inner manholes were collected using a prism dip technique. In this technique internal reflection plates (or prisms),

Table 1

RESULTS OF INFLOW-OUTFLOW BULK WATER SAMPLING

DAY	TIME OF COLLECTION	FLOW MGD	UPSTREAM OF SIPHON			AT MANHOLE 4		
			TOTAL EXTRACTABLES IN MG/1	% FATTY MATTER	% HYDRO-CARBONS	TOTAL EXTRACTABLES IN MG/1	% FATTY MATTER	% HYDRO-CARBONS
6/24/69	3:30 PM - 8:00 AM	1.39	14	45.3	54.7	11	53.8	46.2
6/25/69	8:00 AM - 3:30 PM *	1.43	20	64.8	35.2	11	79.6	20.4
	3:30 PM - 8:00 AM ①	1.43	11	60.4	39.6	13	0	100.0
6/26/69	8:00 AM - 8:00 AM	1.43	12	96.7	3.3	10	91.3	8.7
6/27/69	8:00 AM - 8:00 AM	2.48	29	77.7	22.3	48	64.0	36.0
6/28/69	8:00 AM - 8:00 AM	1.43	36	91.3	8.7	27	92.5	7.5
6/29/69	8:00 AM - 8:00 AM ②	1.47	19	95.7	4.3	16	98.7	1.3

* ① START OF CONTINUOUS SAMPLING, ② END OF CONTINUOUS SAMPLING
(HEXANE-EXTRACTABLE MATTER)

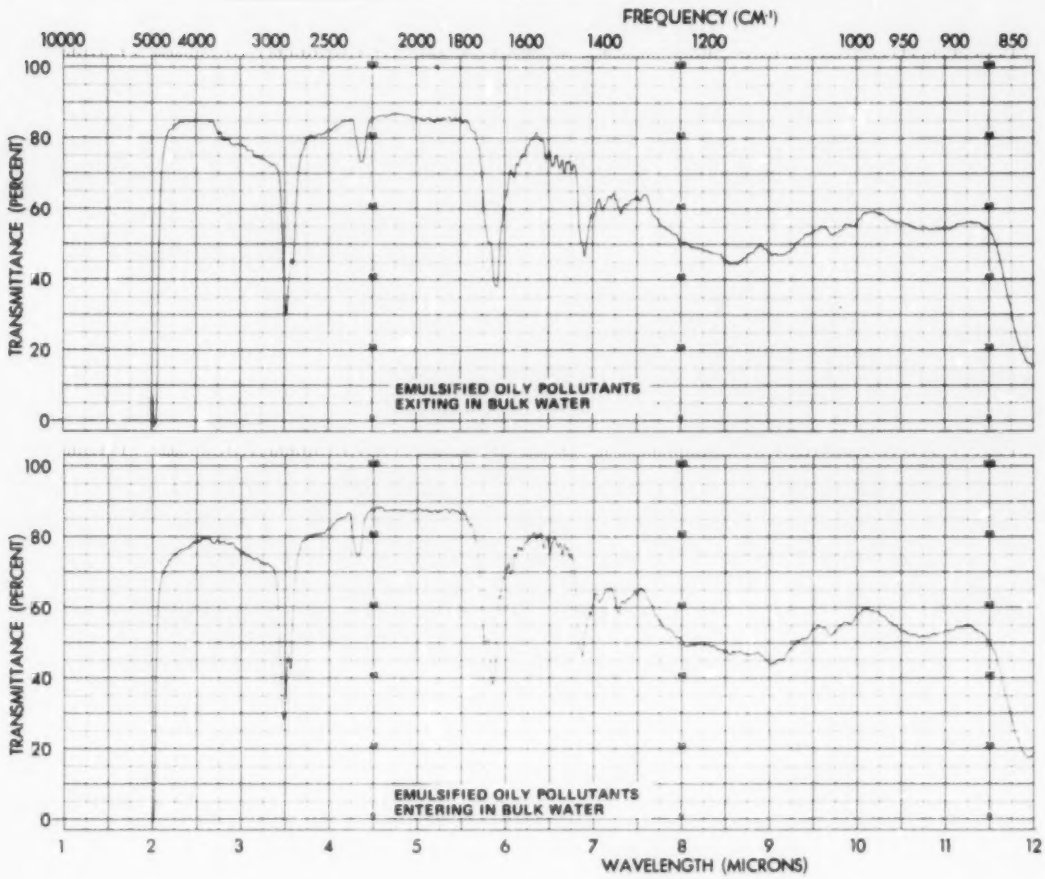


Figure 9 INFRARED SPECTRA OF CHLOROFORM-EXTRACTABLE MATTER IN BULK WATER ENTERING AND EXITING INVERTED SIPHON SECTION OF SANITARY SEWER

commonly fabricated from germanium, are simply dipped slowly in and out of the liquid surface once. The collected surface sample is then analyzed by a spectroscopic technique which is based on multiple internal reflection of light within the prism. Descriptions of all of the sampling techniques developed for use on the Buffalo River Program are given in detail in a separate topical report entitled "Sampling and Identification of Pollutant Oils in Industrial Watercourses" (Reference 4). A typical sequence of infrared spectra characterizing the surface material found in manholes No. 1 through 4 during the 1969 sampling effort is shown in Figure 10. The top trace in this figure shows the diagnostic spectrum of surface layers just upstream of the actual siphon section as determined from prism dip samples taken at manhole No. 1. This spectrum primarily represents products of biological origin with the predominance of fatty materials (for example, triglycerides) and proteins. A simple mixture of cooking greases and proteins (for example, egg whites or vegetable extracts) would match this spectrum almost exactly. The second spectrum from the top in Figure 10 typifies the surface of the very deep column of accumulated oils and greases in manhole No. 2 which most often included some very large vegetable fragments as well. In this spectral trace, one will note that a shift has occurred in one of the major infrared absorption bands from the position representing esters, as in the uppermost trace in Figure 10, to a position more representative of fatty acid byproducts from degradation of biological esters (note the sharp spike in the region around 1700 cm^{-1}). This shift is a strong indication that active bacterial degradation of the materials entering the siphon section was taking place and the odoriferous gases emitted from these manholes further attested to this fact. The third trace from the top in Figure 10 characterizes the surface layers in manhole No. 3 and represents accumulated "skimmings" from the flowing stream. Comparison of this spectrum with that from manhole No. 2 shows that most of the proteinaceous material (typified by absorption bands near 3300, 1650, and 1550 cm^{-1}) is well trapped in the second manhole and does not enter the third manhole standpipe. Otherwise, the oil fractions in both columns are essentially identical. It should be pointed out that the very sharp central spike (in the spectra for manholes No. 2 and 3) characterizing these columns of light oils is not typical of exclusively petroleum-based oils such as diesel fuels or other hydrocarbon fuels. Rather, a mix of such oils with biological products is indicated. It is significant to note that upstream of the sanitary sewer interceptor is a large municipal market place which prepares meats and vegetables for retail trade and provides inputs to the sanitary sewer line. The bottom spectrum in Figure 10 is illustrative of the dramatic improvement in the surface quality of the stream leaving the inverted siphon section. Almost all traces of surface oils and proteins, indeed of any surface debris, are completely eliminated as indicated by the relative absence of large absorption spikes in the infrared trace. However, these data do not bear on the quality of the bulk liquid flowing below. The results of the bulk sampling effort described earlier in this section indicate that the efficiency of the siphon for trapping oil from the bulk liquid is markedly lower than the efficiency noted here for the skimming and trapping of surface oils.

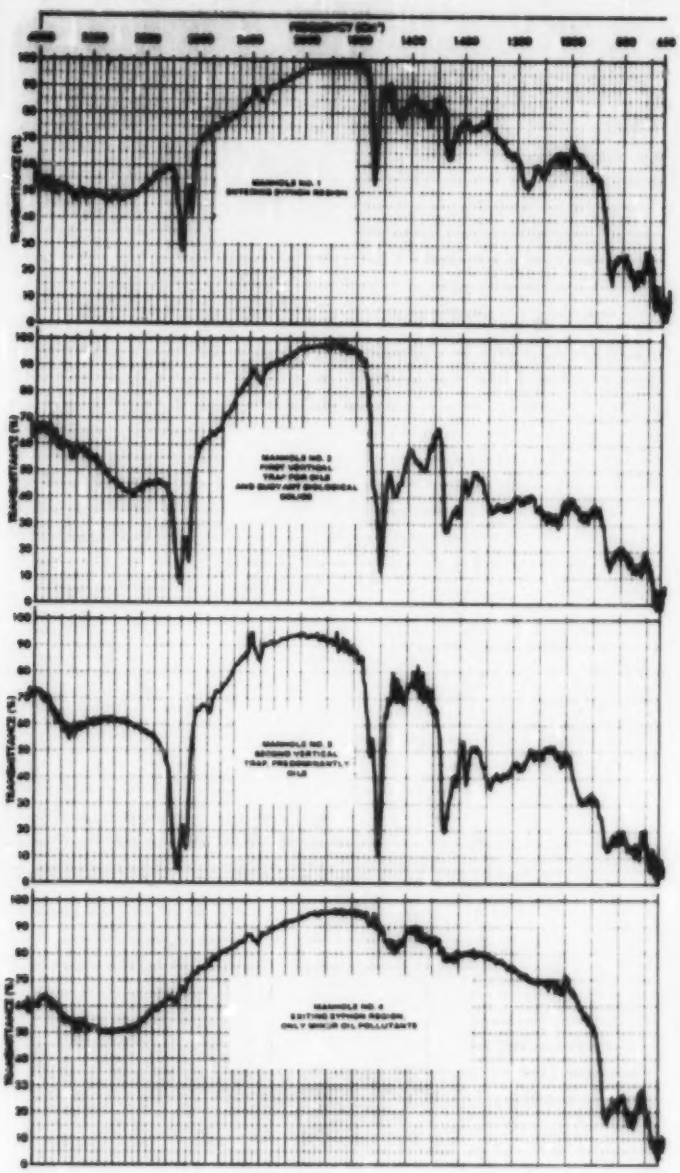


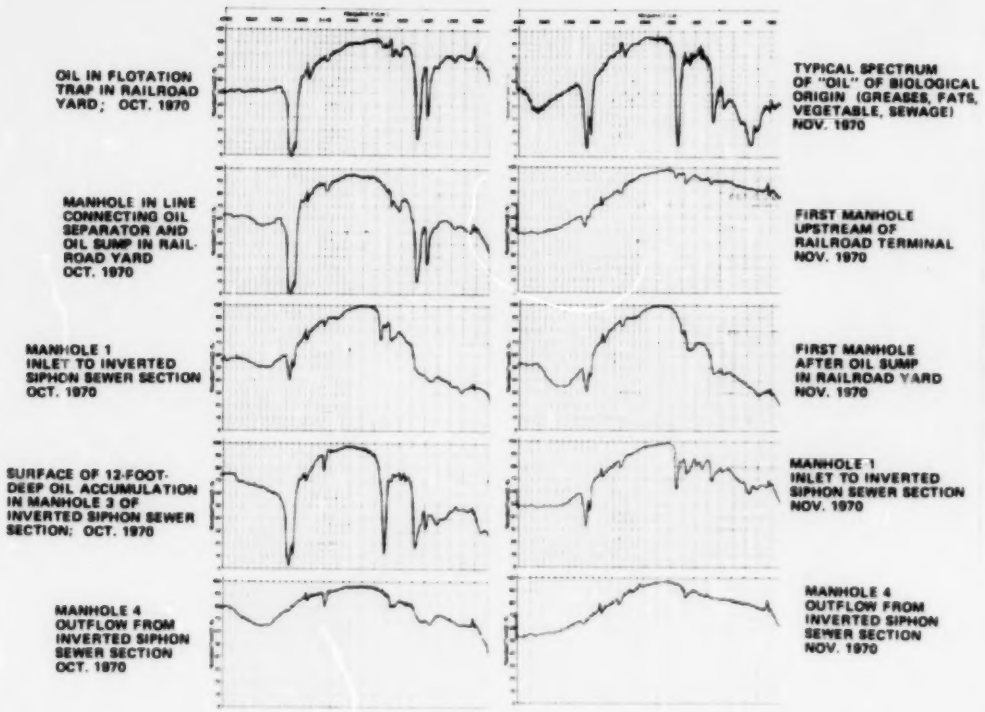
Figure 10

CHARACTERISTIC INFRARED SPECTRA OF POTENTIAL RIVER POLLUTANTS ENTERING, TRAPPED IN, AND EXITING INVERTED SIPHON SANITARY SEWER

Figure 11 presents spectra of samples collected by the prism dip technique during October and November of 1970. The sequence at the left for October 1970 begins (top to bottom) with a sample collected in the flotation trap at the nearby railroad yard. The second sample of the sequence was collected in a manhole in a line connecting an oil separator and an oil sump in the railroad yard. The remaining three spectra of the sequence are for samples collected in manhole 1, manhole 3, and manhole 4 of the inverted siphon. The sequence at the right in Figure 11 begins with the spectrum of a sample of "oil" of biological origin (greases, fats, vegetable, sewage). The sample for the second spectrum of the sequence was collected at the first manhole upstream of the railroad terminal. The third spectrum corresponds to a sample collected at the first manhole after the oil sump in the railroad yard. The remaining two spectra are for samples collected at manhole 1 and manhole 4 of the inverted siphon. Comparison of the various infrared spectral traces presented in the figure shows that the surface material entering the inverted siphon and trapped in the inner manholes is best described as mixed oils of both petroleum and biological origin. The efficiency of the inverted siphon section as a skimmer or "cleanser" for these surface oils is dramatically shown in the two spectra for samples collected from manhole No. 4.

During October of 1970, additional samples were taken upstream and downstream of the inverted siphon sewer in order to estimate the contributions to the oil build-up from the floating films and from the emulsified oil, respectively. The bulk water flow velocity upstream of the inverted siphon section, as measured at manhole No. 1, was (on the same day) 1.23 ft/sec. The water depth was 14 inches. At manhole No. 4, downstream of the inverted siphon, the flow was 1.04 ft/sec with a water depth of 15.5 inches. The volume flow rate was determined by assuming a circular cross-section of the sewer pipe (4 ft diameter) and calculating the area occupied by a segment whose chord was appropriate to the measured water depth. The product of the cross-sectional area of the segment and the stream velocity is the volume flow rate, which averaged about 3.8 ft^3/sec for the stream velocities and depths indicated above.

Based upon calibration data for the prism dip technique, the average surface film thickness of oils entering the siphon was taken as 0.05 micrometer or 500 angstroms. Given this film thickness, and the velocity and geometry of the flow in the pipe, the quantity of surface oil flowing into the inverted siphon section was calculated to be approximately 1/2 gallon per day of biological oils (which the infrared spectra certainly indicated were the predominant components in the floating inflow stream). Thus, over a monthly period, some 15 gallons should be found to accumulate in the inverted siphon section (notably in manhole No. 2) if no other sources existed. For the bulk water samples taken upstream and downstream of the inverted siphon section on the same sampling day, the inflow water concentration was found to be 15.6 ppm extractable oils and the outflow only a slightly lower value of 15.1 ppm extractable oils. Thus, carrying out a very straightforward calculation, it


OIL IN FLOTATION TRAP IN RAILROAD YARD; OCT. 1970
TYPICAL SPECTRUM OF "OIL" OF BIOLOGICAL ORIGIN (GREASES, FATS, VEGETABLE, SEWAGE) NOV. 1970
MANHOLE IN LINE CONNECTING OIL SEPARATOR AND OIL SUMP IN RAILROAD YARD OCT. 1970
FIRST MANHOLE UPSTREAM OF RAILROAD TERMINAL NOV. 1970
MANHOLE 1 INLET TO INVERTED SIPHON SEWER SECTION OCT. 1970
FIRST MANHOLE AFTER OIL SUMP IN RAILROAD YARD NOV. 1970
SURFACE OF 12-FOOT-DEEP OIL ACCUMULATION IN MANHOLE 3 OF INVERTED SIPHON SEWER SECTION; OCT. 1970
MANHOLE 1 INLET TO INVERTED SIPHON SEWER SECTION NOV. 1970
MANHOLE 4 OUTFLOW FROM INVERTED SIPHON SEWER SECTION OCT. 1970
MANHOLE 4 OUTFLOW FROM INVERTED SIPHON SEWER SECTION NOV. 1970

NOTE: ALL SAMPLES COLLECTED BY THE PRISM-DIP TECHNIQUE DURING OCTOBER AND NOVEMBER 1970.

Figure 11

TWO SEQUENCES OF INFRARED SPECTRA CHARACTERIZING POTENTIAL OILY POLLUTANTS OF PETROLEUM AND BIOLOGICAL ORIGIN WITH LIKELIHOOD OF ENTERING SEWER LINE, ACTUAL OILY POLLUTANTS ENTERING AND COLLECTED IN INVERTED SIPHON SECTION OF SEWER, AND SURFACE QUALITY OF "SKIMMED" WATER EXITING INVERTED SIPHON SECTION OF SEWER

could be determined that between 1100 and 1200 gallons of oil were available per month in the inflow bulk water. Since the trapping efficiency for these emulsified or suspended organic pollutants was very low, the actual oil accumulation in the inverted siphon section itself that could be accounted for by the bulk water would amount to only about 30 gallons per month. Thus, the combined amounts of 15 gallons per month from the surface films and 30 gallons per month from the potential contribution from the bulk waters in their natural "sewage" state could not account for the large amounts of oil trapped in the inverted siphon at certain times (e.g., up to 2000 gallons in a 15-day period during the evaluation of the oil detectors as noted in the previous section of this report). On the basis of the combined data presented here and the results presented in a later section, that some 70% of the actual mass accumulated in inner manholes was of petroleum origin and matched, by most analytical criteria, the No. 2 Fuel Oil used regularly adjacent to this inverted sewer line at a railroad refueling terminal, the conclusion seems inescapable that adventitious spills of this material were finding their way into the sewer at times that were not coincident with the monitoring periods of the Buffalo River Project. It is also certain, taking into account the relative efficiencies of trapping of the bulk oils vs. the surface oil films, that the oils accumulated in the vertical manholes must have entered that section as floating oils in very large amounts over very short periods of time.

CHARACTERIZATION OF THE OIL POLLUTANTS ACCUMULATED IN THE INNER MANHOLES OF THE INVERTED SIPHON

Samples collected in October of 1970 included samples of the deep oil accumulations in Manholes Nos. 2 and 3 of the inverted siphon in an effort to determine the characteristics of the trapped oil. Manhole No. 2 was sampled at depths of 1/2 meter and 2 meters from the liquid surface. Sampling at greater depths was frustrated by large amounts of debris and encrusted material. Manhole No. 3 was sampled at depths of 1/2 meter, 2 meters and 4 meters. These samples were then subjected to analysis by gas chromatography and by infrared spectroscopy. During the gas chromatographic analyses, the following conditions were used which should be recorded. The column was a 10% silicone column labelled UCW9880, 6 feet in length. Dual flame ionization detectors were used at 300°C. The injection port temperature was 260°C. The column temperature was programmed from 100°C to 250°C at the rate of 15°C per minute. A sample volume for injection was 1.5 microliters plus or minus 0.2 microliter. During a series of chromatographic analyses of various hydrocarbon and fuel standards, and of the sewer samples themselves, the instrument attenuation was varied from 1 to 16 and the range setting was 10^4. In addition to the samples taken from the inverted siphon, the following samples were analyzed: hydrocarbon standards of C_6 through C_{16} which were normal hydrocarbons to establish the nominal boiling point range (the source of these standards was the Hewlett-Packard Corporation); standard No. 2 fuel oil provided from an oil refinery and known to have a slightly higher boiling point range than the narrower diesel fuel cut; South Louisiana Crude Oil; and Paraffin oil containing predominantly high boiling hydrocarbons with chain lengths greater than C_{16}.

Gas chromatograms characterizing the oily pollutants accumulated at various levels in manholes No. 2 and No. 3 of the inverted siphon sewer are presented in Figure 12. The significant results derived from these chromatograms are summarized briefly as follows: in manhole No. 2 at the 1/2 meter depth, the chromatogram contained two low boiling point components, but the balance was nearly identical to No. 2 Fuel Oil. At the 2 meter depth in this same manhole, the chromatogram was nearly identical to that of the 1/2 meter depth sample, but with the absence of the low boiling point compounds. The lower boiling point components, since they were zoned preferentially in the upper layers, were of lower density than the other oil components. Because these components were of lower boiling point and exposed to the atmosphere they were probably being depleted by evaporation. This accounts for the occasional smell of fuel oil in this manhole. For manhole No. 3, chromatographic analysis showed the 1/2 meter depth sample to be nearly identical to No. 2 Fuel Oil as did the analyses for the samples taken at depths of 2 meters and 4 meters.

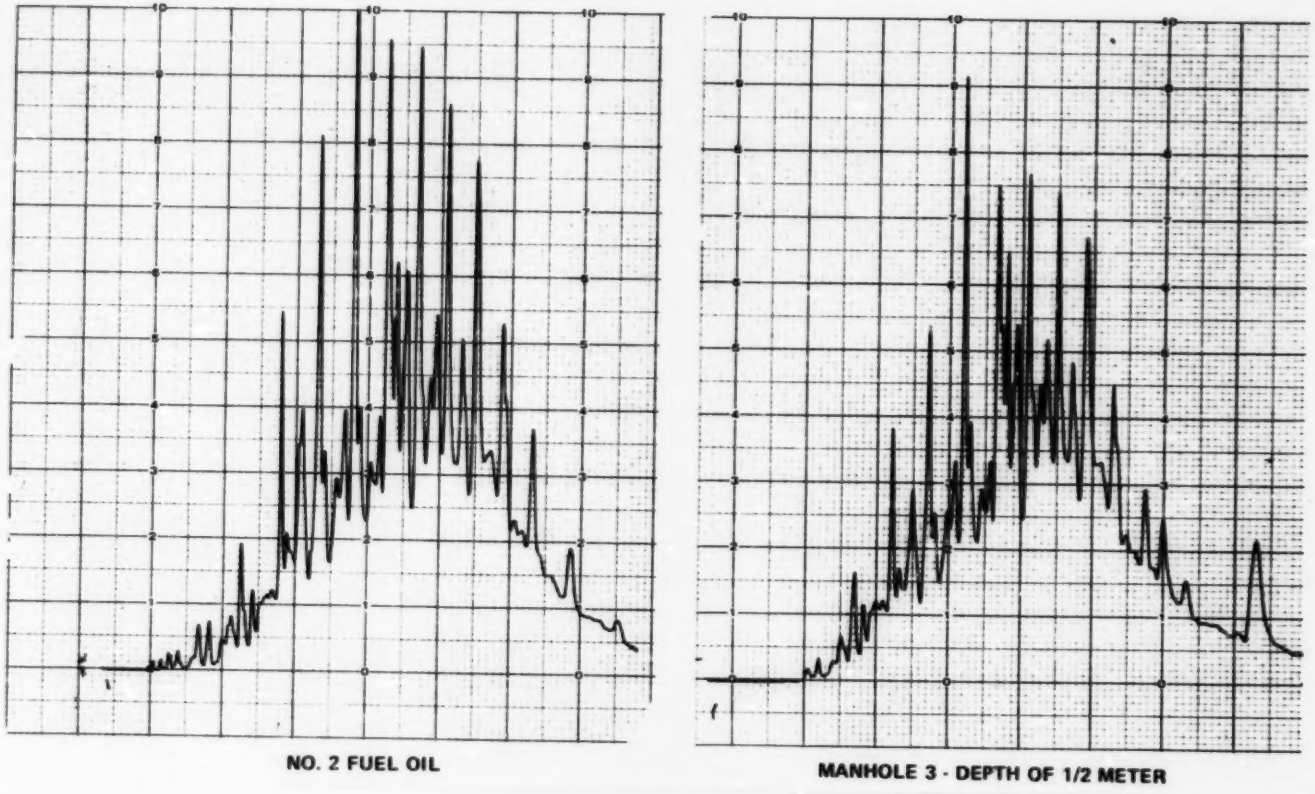
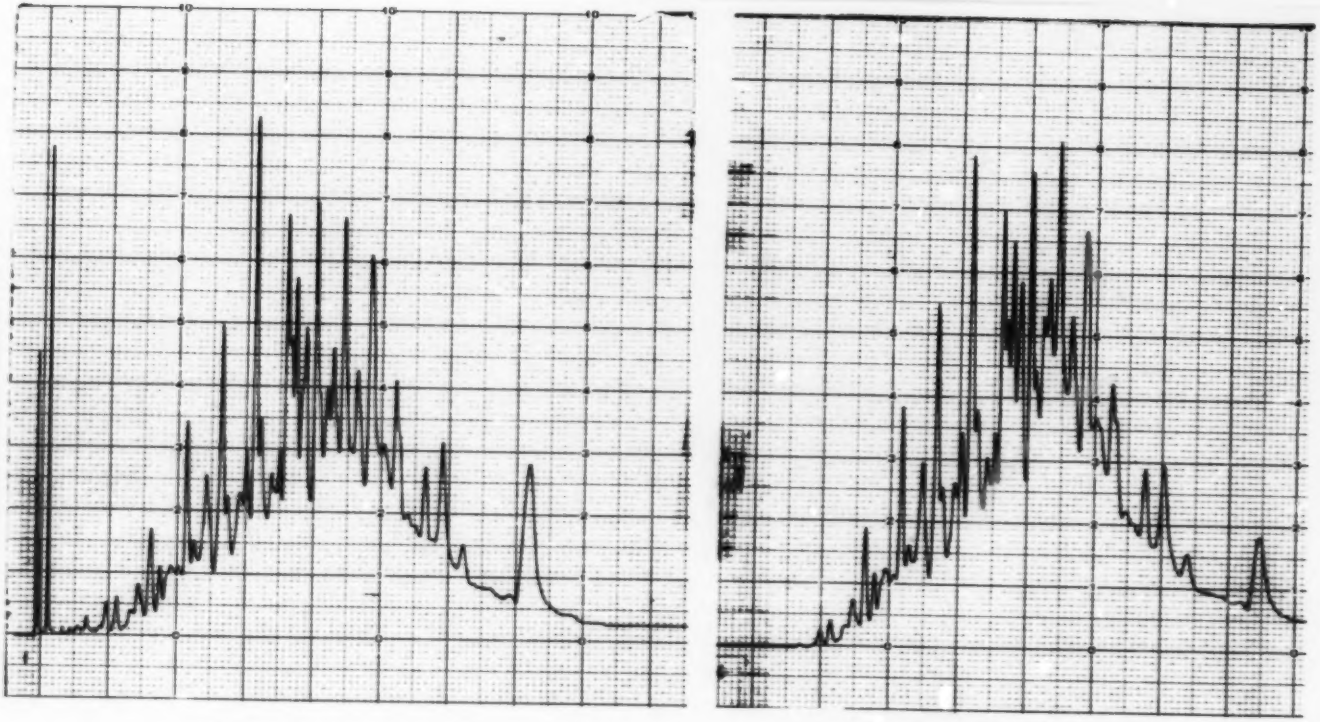


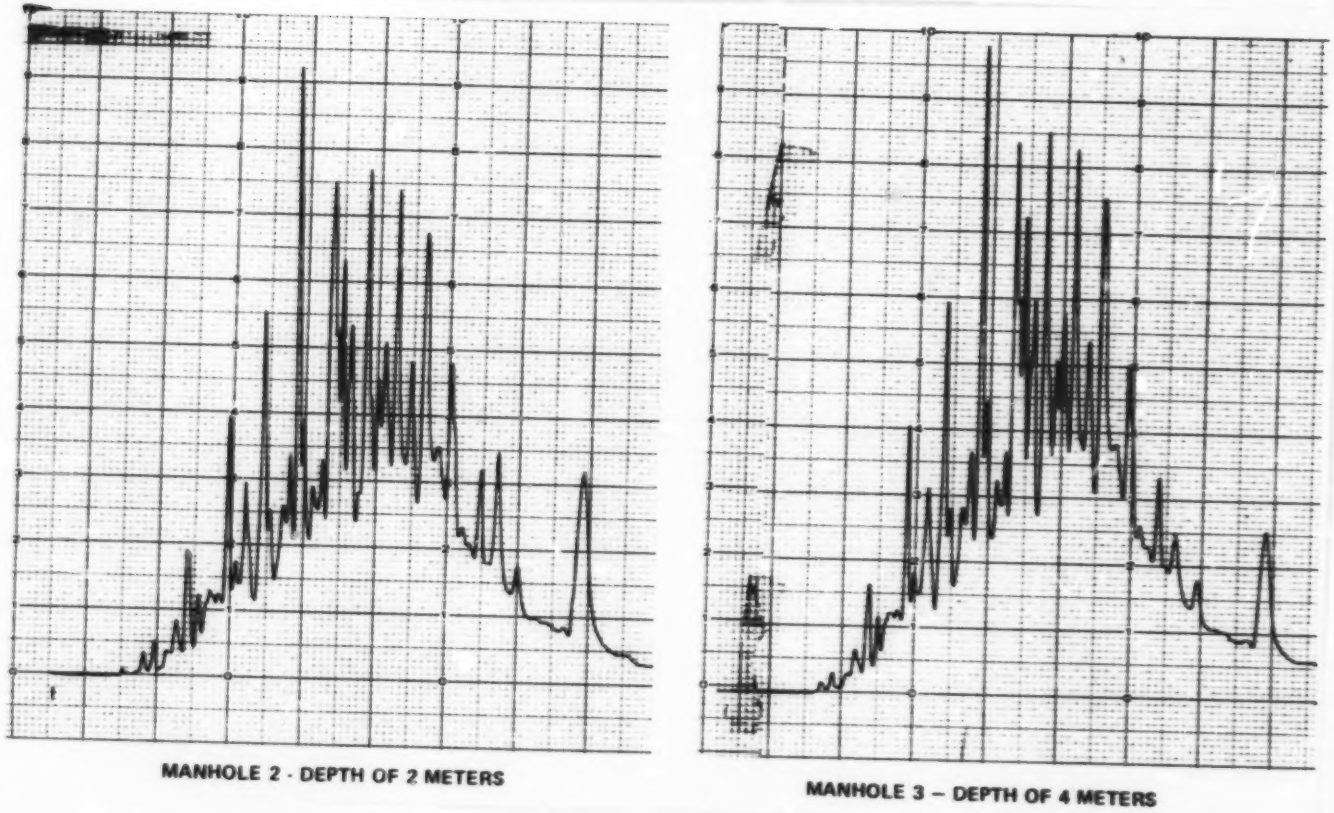
Figure 12 GAS CHROMATOGRAMS CHARACTERIZING THE OILY POLLUTANTS ACCUMULATED AT VARIOUS LEVELS IN MANHOLES 2 AND 3 OF THE INVERTED SIPHON SEWER (Sheet 1 of 3)



MANHOLE 2 - DEPTH OF 1/2 METER

MANHOLE 3 - DEPTH OF 2 METERS

Figure 12 GAS CHROMATOGRAMS CHARACTERIZING THE OILY POLLUTANTS ACCUMULATED AT VARIOUS LEVELS IN MANHOLES 2 AND 3 OF THE INVERTED SIPHON SEWER (Sheet 2 of 3)



MANHOLE 2 - DEPTH OF 2 METERS

MANHOLE 3 – DEPTH OF 4 METERS

Figure 12 GAS CHROMATOGRAMS CHARACTERIZING THE OILY POLLUTANTS ACCUMULATED AT VARIOUS LEVELS IN MANHOLES 2 AND 3 OF THE INVERTED SIPHON SEWER (Sheet 3 of 3)

Using the attenuation data recorded during the chromatographic analyses of the various hydrocarbon oil standards, it was possible to estimate the approximate concentrations of No. 2 Fuel Oil in each of the samples from manholes No. 2 and No. 3. Assumptions made in this estimate were: (1) that the sample sizes were constant, and (2) that the chromatogram of the No. 2 Fuel Oil standard represented 100% of the injected sample volume. For manhole No. 2 at the 1/2 meter depth, approximately 70% of the volume of the sample was represented by No. 2 Fuel Oil and at the 2 meter depth a similar result was obtained. For manhole No. 3 (the second manhole encountered by floating oils entering the inverted siphon of the sewer) at the 1/2 meter depth, again approximately 70% of the volume was represented by No. 2 Fuel Oil. At the 2 meter depth, however, the chromatogram indicated essentially 100% No. 2 Fuel Oil, whereas at the 4 meter depth, the volume fraction was again down to some 70%.

From the above analysis it is apparent that the biological components represented at most 30% of the oils entering and trapped in the inverted siphon section of the sanitary sewer and that these were preferentially accumulated in Manhole No. 2 first. When Manhole No. 2 was full, they then entered Manhole No. 3. The large volume of petroleum oil representing the mid depths in Manhole No. 3 most likely resulted from an accidental or surreptitious petroleum discharge into the sewer line from the nearby railroad yard. Later gas chromatograms of samples collected directly from the railroad terminal (from the storage pump and from the oil sump and separator) showed that the chromatograms of that material were identical to our No. 2 Fuel Oil standard and to the material found accumulated in the inverted siphon sewer section.

Figure 13 is a collection of infrared spectra of the same samples used in the chromatographic analyses discussed above. Comparing the traces from Manhole No. 2 with those from Manhole No. 3, it will be noted that a difference exists in the relative intensities of the absorption bands correlating with straight chain hydrocarbons of petroleum origin ($2900\ cm^{-1}$) and with the ester bands for the highly oxygenated oils of biological origin ($1700\ cm^{-1}$). When the ratios of the intensities of these two bands were obtained, Manhole No. 2 showed ratios of 1.6 at the 1/2 meter depth and of 1.7 at the 2 meter depth, while Manhole No. 3 showed ratios of 2.3, 2.1, and 2.4 at the 1/2, 2 and 4 meter depths respectively. In this comparison, a low ratio indicates more carbonyl groups. Therefore, the oil in Manhole No. 2 is more highly oxygenated, or has more oxygenated material mixed with it, than the oil making up the volume in Manhole No. 3. These results confirm the conclusions from the gas chromatography discussed above. Intercomparison of the infrared spectra of the oils from the various depths in each manhole, shows no substantial differences. Thus, there has been a good solubilization or admixing of the biological fractions with the petroleum oil fractions in each vertical column.

As a final check on the separability of the oils that accumulated in these two vertical standpipes, typical chemical saponifications were

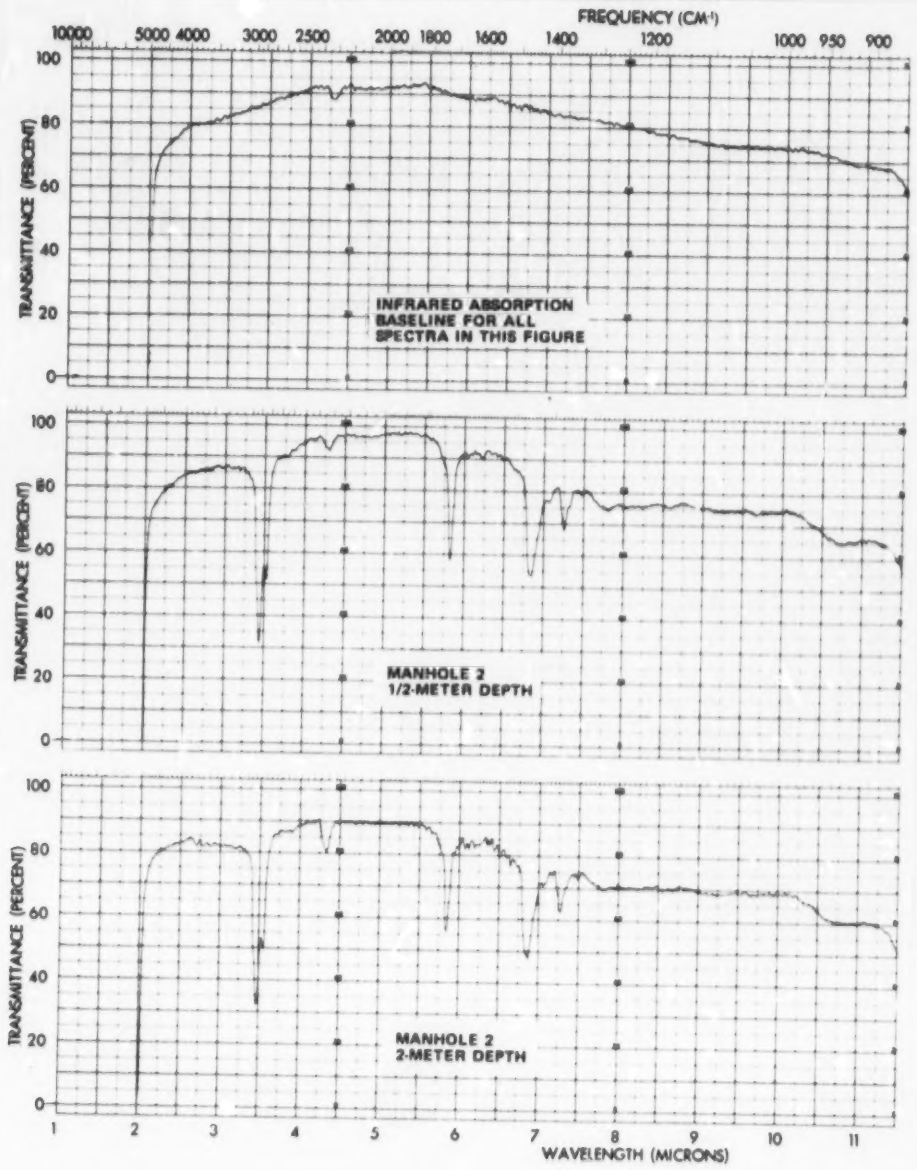

FREQUENCY (CM⁻¹)
10000 5000 4000 3000 2500 2000 1800 1600 1400 1200 1000 950 900
TRANSMITTANCE (PERCENT)
INFRARED ABSORPTION BASELINE FOR ALL SPECTRA IN THIS FIGURE
MANHOLE 2 1/2-METER DEPTH
MANHOLE 2 2-METER DEPTH
WAVELENGTH (MICRONS)

Figure 13 INFRARED SPECTRA CHARACTERIZING THE OILY POLLUTANTS IN MANHOLES 2 AND 3 OF THE INVERTED SIPHON SEWER (Sheet 1 of 2)

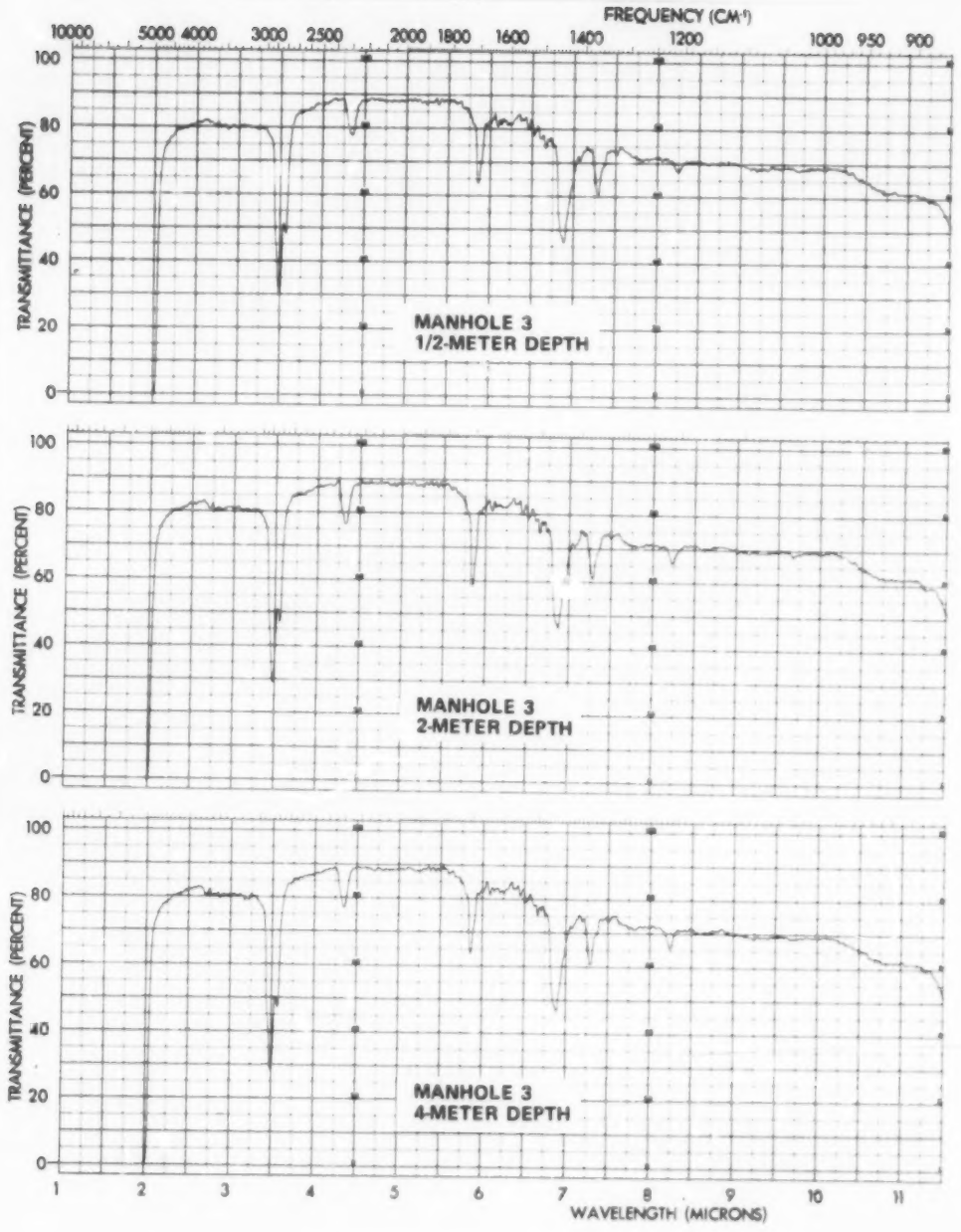

FREQUENCY (CM⁻¹)
10000 5000 4000 3000 2500 2000 1800 1600 1400 1200 1000 950 900
TRANSMITTANCE (PERCENT)
100 80 60 40 20 0
MANHOLE 3
1/2-METER DEPTH
MANHOLE 3
2-METER DEPTH
MANHOLE 3
4-METER DEPTH
1 2 3 4 5 6 7 8 9 10 11
WAVELENGTH (MICRONS)

Figure 13 INFRARED SPECTRA CHARACTERIZING THE OILY POLLUTANTS IN MANHOLES 2 AND 3 OF THE INVERTED SIPHON SEWER (Sheet 2 of 2)

undertaken on material from each of the manholes. Figure 14 shows infrared spectra of variously saponifiable fractions of the oil accumulated in Manhole No. 3 of the inverted siphon sewer. These traces illustrate the simultaneous presence of oils of both biological and petroleum origin. The procedure for preparing the samples corresponding to the traces in Figure 14 was as follows. First, some ethyl alcohol was saturated with sodium hydroxide and then the base-saturated alcohol added to a sample of oil taken directly from the No. 3 manhole. In order to separate the saponified solids from the mixed sample, centrifugation for five minutes at 1200 rpm was carried out. The uppermost infrared scan in Figure 14 is of the supernatant non-saponifiable oil fraction of petroleum origin in this sample and represented some 70% of the volume. The central scan in Figure 14 was produced by extraction of this supernate with acetone, alcohol, and chloroform to leave a solid white residue of tiny solid matter that had not been efficiently separated from the supernate during centrifugation. This represents material only partially saponified, or partially solidified by the reaction with sodium hydroxide. The lowermost spectrum was produced from the solids as filtered from the bottom slurry collected during the centrifugation and washed with acetone, alcohol, and chloroform. This material accounted for approximately 25% of the total volume of the oils when examined by this chemical technique.

As a result of the 1969 and 1970 sampling programs and the associated analyses of the collected samples a number of significant conclusions can be drawn concerning the oil trapping characteristics of inverted siphon configurations. For surface-borne oils the trapping efficiency is nearly 100 percent, while for emulsified oils in the bulk water the trapping efficiency is generally only a few percent and probably 20 percent at best. The overall trapping characteristics of the inverted siphon are summarized in Figure 15.

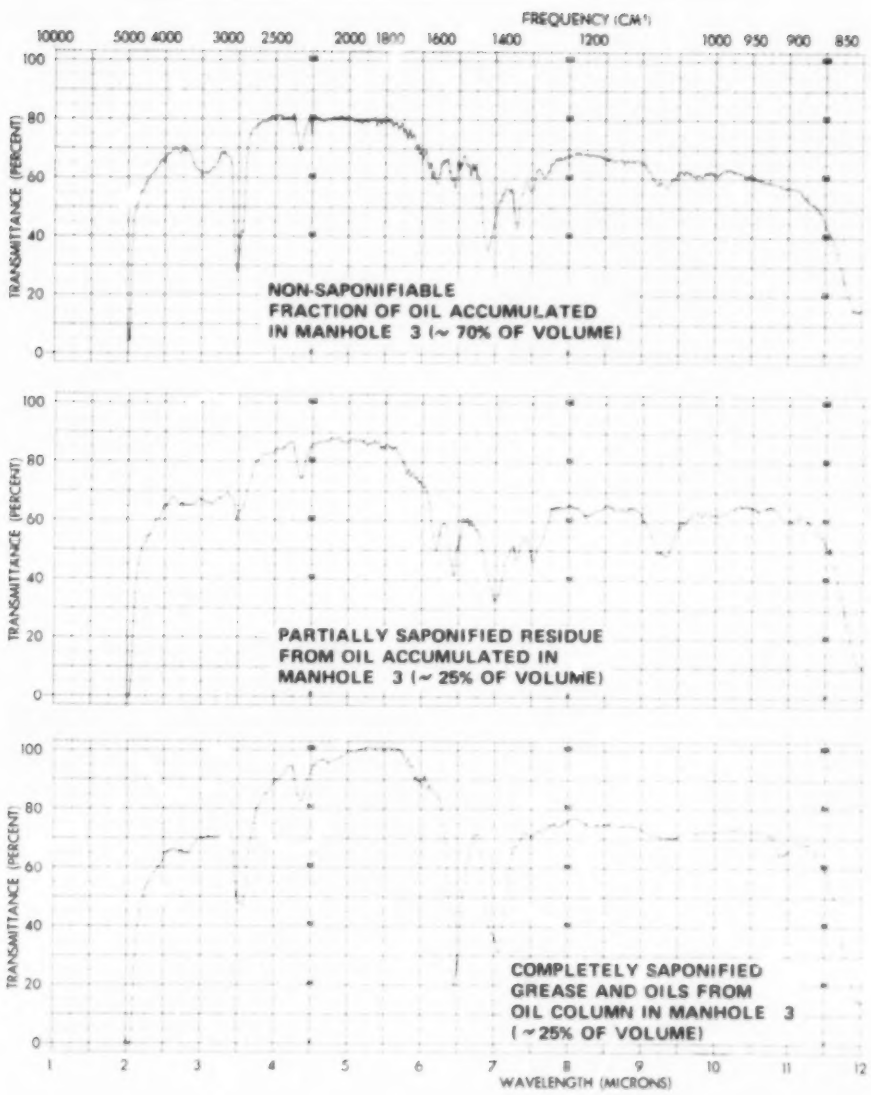

FREQUENCY (CM⁻¹)
10000 5000 4000 3000 2500 2000 1800 1600 1400 1200 1000 950 900 850
TRANSMITTANCE (PERCENT)
NON-SAPONIFIABLE
FRACTION OF OIL ACCUMULATED
IN MANHOLE 3 (~ 70% OF VOLUME)
PARTIALLY SAPONIFIED RESIDUE
FROM OIL ACCUMULATED IN
MANHOLE 3 (~ 25% OF VOLUME)
COMPLETELY SAPONIFIED
GREASE AND OILS FROM
OIL COLUMN IN MANHOLE 3
(~25% OF VOLUME)
WAVELENGTH (MICRONS)

Figure 14 INFRARED SPECTRA OF VARIOUSLY SAPONIFIABLE FRACTIONS OF THE OIL ACCUMULATED IN MANHOLE 3 OF THE INVERTED SIPHON SEWER, ILLUSTRATING THE SIMULTANEOUS PRESENCE OF OILS OF BOTH BIOLOGICAL AND PETROLEUM ORIGIN

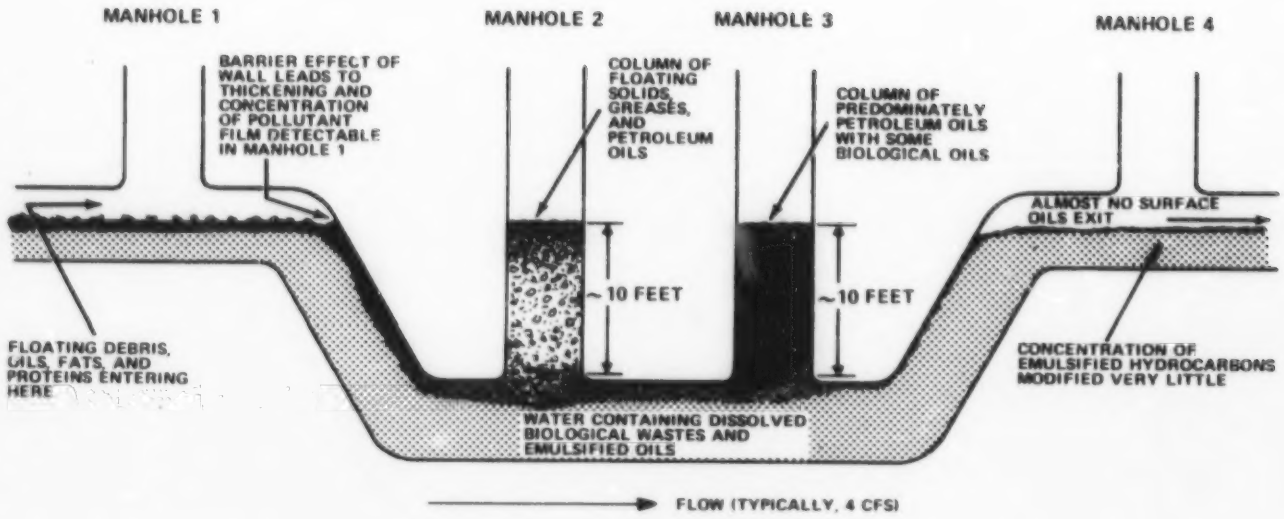

MANHOLE 1
MANHOLE 2
MANHOLE 3
MANHOLE 4
BARRIER EFFECT OF WALL LEADS TO THICKENING AND CONCENTRATION OF POLLUTANT FILM DETECTABLE IN MANHOLE 1
COLUMN OF FLOATING SOLIDS, GREASES, AND PETROLEUM OILS
COLUMN OF PREDOMINATELY PETROLEUM OILS WITH SOME BIOLOGICAL OILS
ALMOST NO SURFACE OILS EXIT
~10 FEET
~10 FEET
FLOATING DEBRIS, OILS, FATS, AND PROTEINS ENTERING HERE
CONCENTRATION OF EMULSIFIED HYDROCARBONS MODIFIED VERY LITTLE
WATER CONTAINING DISSOLVED BIOLOGICAL WASTES AND EMULSIFIED OILS
FLOW (TYPICALLY, 4 CFS)

Figure 15 INVERTED SIPHON SECTION OF SANITARY SEWER AND ITS FUNCTION AS AN OIL TRAP FOR SURFACE-LOCALIZED POLLUTANTS

MODEL STUDIES

To investigate the oil trapping efficiency of configurations other than the specific inverted siphon studied under this program, it was deemed useful to construct scale models of proposed configurations to permit their evaluation in the laboratory at much less cost and under a greater variety of conditions (water and oil flow rates) than would be possible for full-scale systems. However, construction of models scaled in linear dimensions alone is not sufficient to predict the trapping characteristics of full-size configurations, since oil and water flow rates, as well as time, must be scaled. In order to determine which scaling laws are valid for predicting the flow behavior of oil-water systems, an investigation was undertaken of scaled models of the inverted siphon at Memorial Drive and Gibson Street, since much data has been acquired on the behavior of this particular siphon.

THEORY

Modeling of fluid flow systems involves the application of appropriate scaling laws so that geometrically similar systems constructed at different scales will have flows which are dynamically similar. Usually one seeks a dimensionless ratio which, for the same value for all models, insures that the hydrodynamic flows are similar. Two ratios commonly used in fluid flow modeling are the Froude number and the Reynolds number. The appropriateness of either of these numbers depends on the specific system to be modeled. In general, for two or more models at different scales, it is not possible to have the Froude number the same for all models and at the same time have the Reynolds number the same.

For systems in which the predominant forces are inertia and gravity, the Froude number is generally applicable for modeling since it is the ratio of the inertia force to the gravity force. A general expression for the Froude number is:

$$F = \frac{v^2}{g\ell} \qquad (1)$$

where v is the flow velocity, ℓ is a characteristic length or distance, and g is the acceleration due to gravity. For systems in which two fluids of slightly different density are considered (e.g., oil and water as in the present modeling situation), a somewhat different form of the Froude number applies and is expressed as:

$$F = \frac{v^2 \rho}{g \ell \Delta\rho} \qquad (2)$$

where ρ is the density of one of the fluids and $\Delta\rho$ is the difference in the densities of the two fluids.

The Reynolds number, which is the ratio of the inertia force to the viscous force, is generally applicable for systems in which these are the predominant forces. The Reynolds number is expressed as:

$$F = \frac{\rho v \ell}{\mu} \tag{3}$$

where ρ, v, and ℓ are, as before, density, velocity and length respectively, and μ is the viscosity.

For two geometrically similar models a and b, Froude scaling requires that:

$$\frac{v_a^2 \rho_a}{\ell_a \cdot \Delta\rho_a} \qquad \frac{v_b \rho_b}{\ell_b \cdot \Delta\rho_b} \tag{4}$$

where the subscripts denote the corresponding models. If the same two fluids are used in both models, the required relationship between velocities and lengths becomes:

$$\frac{v_a}{v_b} = \left(\frac{\ell_a}{\ell_b}\right)^{1/2} \tag{5}$$

On the other hand, for the same two models, Reynolds scaling requires that:

$$\frac{\rho_a v_a \ell_a}{\mu_a} = \frac{\rho_b v_b \ell_b}{\mu_b} \tag{6}$$

Again, if the same fluids are used in both models, this relationship becomes simply:

$$\frac{v_a}{v_b} = \frac{\ell_b}{\ell_a} \tag{7}$$

Clearly, for the two given models, these scaling laws are in conflict if we use the same two fluids in both models. Theoretically, both scaling laws can be satisfied if:

$$\frac{\ell_a^3 \rho_a \Delta\rho_a}{\mu_a^2} = \frac{\ell_b^3 \rho_b \Delta\rho_b}{\mu_b^2} \tag{8}$$

However, model fluids that would fulfill this requirement are virtually impossible to find. Therefore, one hopes that either the gravity or

viscous force will clearly predominate so that only one of the scaling laws need be satisfied to insure similarity in the dynamic behavior of the two systems.

For an inverted siphon situation, gravity effects can be expected to play an important role in oil trapping since it is the buoyant force on the oil that causes it to rise into the inner manhole chambers (see Manholes 2 and 3, Figure 1). On the other hand, surface oil which accumulates upstream of the siphon (in the area of Manhole 1, Figure 1) would not enter the siphon section unless friction forces were in play. If no oil accumulated on the water surface upstream of the siphon, one might conclude that the surface oils are carried into the siphon by inertia effects, and in this case, that viscous forces are less important.

DESCRIPTION OF MODELS

In order to determine the applicable scaling law for modeling inverted siphon configurations, two models of the inverted siphon at Memorial Drive and Gibson Street (Figure 1) were constructed, one at 1/12 scale and the other at 1/24 scale. Since the diameter of the main pipe in the Memorial Drive inverted system is 48 inches, the corresponding model dimensions were 4" and 2". While a single model would be sufficient to test scaling relationships by comparison with the behavior of the full-scale system on Memorial Drive, two laboratory models provided a more practical approach and allowed greater flexibility in selecting oil and water flow rates. The detailed measurements required to establish scaling relationships would have been virtually impossible to obtain in the full-scale siphon and neither the oil flow nor the water flow could be controlled to desired levels or maintained constant over sufficiently long test periods.

The general arrangement of the two models and the associated piping and tanks is shown in Figure 16. Water was supplied to the models by a 400-gallon capacity galvanized tank. A constant flow in the system was obtained by maintaining a fixed water level in a 95-gallon tank fitted with a V-notched weir. To change the flow rate as required for different tests, the effective head on the weir was adjusted accordingly. A valve arrangement permitted the flow to be directed to either of the two system models. The circular sections of the siphon models were constructed from clear plexiglas tubes in order to permit the flow characteristics to be observed and to allow measurements to be made easily. The square vertical manhole chambers were constructed from flat plexiglas sheets. The 45-degree bends consisted of standard plastic elbow fittings. The required fittings were not available in clear plastic, but this fact did not interfere with the required measurements and observations. The flow through the models was discharged into a catch tank. For each model, a port was located approximately 10 feet upstream of the first manhole chamber to allow

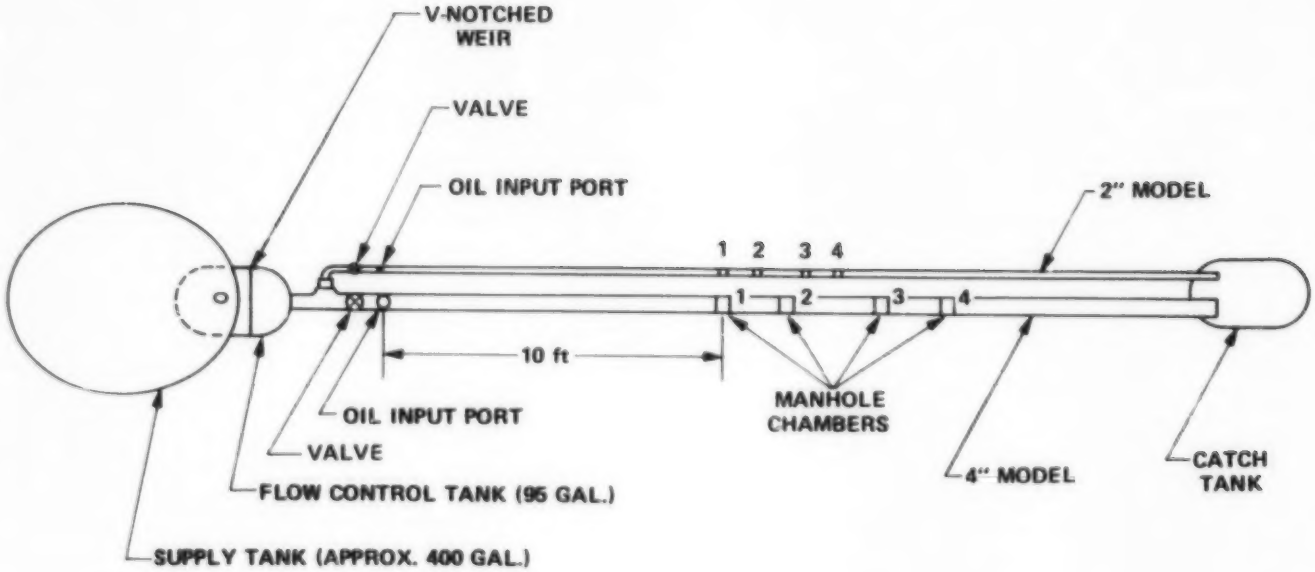


Figure 16 INVERTED SIPHON MODEL ARRANGEMENT (TOP VIEW)

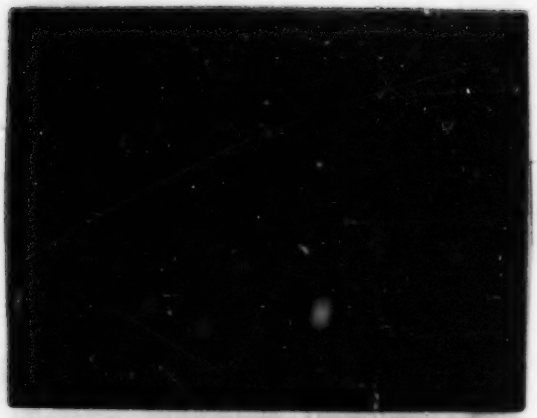
oil to be introduced at controlled flow rates. The slope of the models was set equal to the slope of the actual inverted siphon located on Memorial Drive.

Photographs of the models taken as construction was nearing completion are presented in Figure 17.

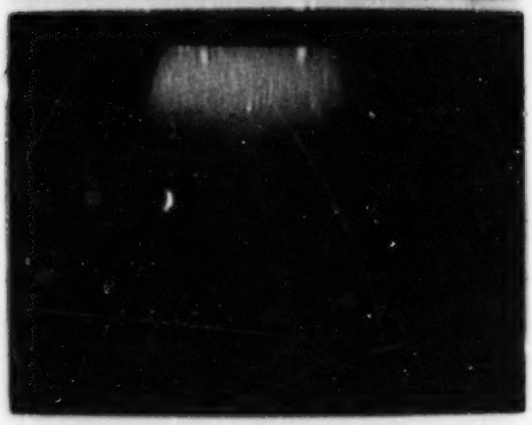
The water flow control system was calibrated by measuring the volumetric flow rate for various water levels in the flow control tank. The maximum flow rate used in any of the model tests was approximately 10.6 gallons/minute for the four-inch model. For Froude scaling, this model flow corresponds to a flow rate of about 5300 gallons/minute in the actual full-scale siphon, or about 7.6 million gallons/day, which is greater than the flow rate measured in the actual siphon at any time during the program except under peak flow conditions encountered during a storm. For Reynolds scaling, the 10.6 gallons/minute value corresponds to a flow rate of about 125 gallons/minute in the actual siphon which is lower than any value measured during the program. However, since the appropriate scaling relationships were to be verified by the test in the two models, it wasn't necessary to scale the flow rates to those of the actual siphon. Of course, once the correct scaling relationships are established, it is necessary to have a sufficient flow capacity in the model to properly scale the actual siphon flows in order to predict the behavior of the full-scale system. The scaling studies showed that Froude scaling rather than Reynolds scaling was more applicable to the case of the inverted siphon so that present model flow capability is more than adequate to permit scaling to full-scale conditions.

Oil was supplied to the input ports (see Figure 16) from a five-gallon reservoir tank. The desired flow rates were controlled by a precision needle valve which permitted fine flow adjustments to be made as required. Oil inputs of up to 0.4 gallons/minute were used in the scaling tests. For Froude scaling with the four-inch model, this rate is equivalent to an oil input rate of 200 gallons/minute in the actual sewer system. Oil discharges into the actual sewer at this high rate were never observed. For typically observed water flows of 1 to 2 feet/sec. in the actual sewer, a surface oil slick 1 to 2 inches thick would be required to correspond to an oil volumetric flow rate of 200 gallons/min.

In order to permit ease of measurement and observation for the model tests, a red dye was added to the oil. This dye was of a type commonly used for coloring petroleum derivatives.



VIEW OF TWO-INCH MODEL SHOWING SUPPLY AND FLOW CONTROL TANKS



VIEW OF MANHOLE CHAMBERS FOR TWO-INCH MODEL

VIEW OF FOUR-INCH MODEL

Figure 17 PHOTOGRAPHS OF INVERTED SIPHON MODELS

MODEL TESTS

The initial model tests were based on Froude scaling of the water flow conditions observed in the real inverted siphon sewer section on Memorial Drive in October 1970. For Froude scaling, it can be shown from Equation (2) that the volumetric flow rate, Q, scales as:

$$\frac{Q_A}{Q_M} = \left(\frac{\ell_A}{\ell_M}\right)^{5/2} \tag{9}$$

where ℓ is a characteristic length and the subscripts A and M refer to the actual siphon and the model system respectively. It can also be shown from Equation (2) that for Froude scaling, the time, t, and the velocity, v, scale as:

$$\frac{t_A}{t_M} = \frac{v_A}{v_M} = \left(\frac{\ell_A}{\ell_M}\right)^{1/2} \tag{10}$$

The appropriate Froude scaling factors for the 1/24 scale (two-inch) model and the 1/12 scale (four-inch) model relative to the actual inverted siphon are presented in Table 2.

Table 2

FROUDE SCALING FACTORS FOR INVERTED SIPHON MODELS

	FULL SCALE SIPHON (48")	1/24 SCALE MODEL 2"	1/12 SCALE MODEL 4'
CHARACTERISTIC LENGTH, L	1	1/24	1/12
CHARACTERISTIC TIME, t	1	0.204	0.289
VELOCITY, v	1	0.204	0.289
FLOW RATE, Q	1	0.000354	0.00200

Using the indicated scaling factors, water flow rates were selected for the model tests which would approximate the water flow rates observed in the actual inverted siphon section during October 1970. The condition prevailing at that time was representative of relatively low flow conditions of about 2.5×10^6 gallons per day as calculated from measured values of average flow velocity (1.23 ft/sec) and water depth (14 inches) in the sewer line upstream of the siphon section. The flow

rates used for the initial Froude modeling tests are presented in Table 3, along with the equivalent flow rate for the full-scale siphon. siphon.

Table 3

MODEL FLOW RATE FOR INITIAL FROUDE SCALING TESTS

	1/24 SCALE MODEL	1/12 SCALE MODEL	FULL SCALE SIPHON
Q_w, WATER	0.63 GAL/MIN	3.53 GAL/MIN	1770 GAL/MIN
Q_o, OIL	0.00112 GAL/MIN	0.00633 GAL/MIN	3.16 GAL/MIN

The oil flow rates used for the model tests are also presented in Table 3. These flow rates do not correspond to the oil flow rates observed in the full-scale system in October 1970. At that time, flow for surface oil was determined to be only about one-half gallon per day or 0.00035 gallons per minute. At such low oil flows, it would require years to fill one of the vertical chambers of the inner manholes with trapped oil. Thus, a larger flow rate was selected which might provide more reasonable test times and at the same time serve to simulate the situation of a rather substantial oil discharge into the sewer system. As indicated in the table, the oil flows selected for the initial model runs corresponded to an oil discharge slightly more than three gallons per minute in the full-scale siphon.

In each model test, the desired water flow rate was first established and then at "zero" time, the oil was introduced into the model upstream of the first manhole through the oil input port (see Figure 16) at a previously selected rate. No. 2 fuel oil (dyed red) was used for all the model runs discussed in this report. The oil nozzle was positioned just above the water surface so that the oil entered the water stream with only a small vertical velocity component. All oil was observed to surface immediately and no traces of oil could be detected in the bulk water. This was the desired condition since the purpose of the tests was to observe the characteristics of the inverted system configuration for trapping surface oils.

There were certain similarities in the behavior of the models at the scaled flow rates indicated in Table 3. Before any oil entered the lower section of the siphon, a substantial amount of oil pooled on the water surface upstream of the first 45° (downward) bend. In the case of the two-inch model, oil began to enter the siphon section when the surface oil pool backed up near the oil input port, whereas in the case of the four-inch model, oil pooled past the oil input port all the way to the water flow-regulating tank (Figure 16). This difference occurred because the distances from Manhole No. 1 to the oil input port were not scaled and were the same for both models. In the design

of the models, it was not considered important to scale this distance, since this distance should not change the oil trapping behavior of the system. However, at the water flow rates used in these initial model runs, the positions of the input oil ports became an important factor. Subsequent tests were conducted at higher water flow rates and the oil pool did not back up as far for either model.

In both models, once oil began to flow into the lower section of the siphon, virtually all of the oil was trapped in the vertical chamber of Manhole No. 2, with only trace amounts being carried into Manhole No. 3 and farther downstream. When Manhole No. 2 was filled with oil, then oil began entering Manhole No. 3. Again, most of the flowing oil was trapped by the third manhole with only trace amounts being lost. Once the two inner manhole chambers were filled, no additional oil was trapped by the siphon and all oil entering the siphon section was carried into the downstream collection tank.

In order for a scaling law to be valid, it must be able to predict all important aspects of the behavior of the full-scale system from observations made on the model. In the present case, this requirement includes predictions of the times for the vertical inner manhole chambers to fill with oil. At the flow rates selected for the initial test (Table 3), the two-inch model required 620 minutes for Manhole No. 2 to become one-third full of oil. (Zero time corresponds to the instant when oil was introduced into the oil input port.) With properly scaled similar initial conditions for the four-inch model, it required 530 minutes for Manhole No. 2 to become one-third full of oil. For Froude scaling (see Table 2), the data for the two-inch model predict that for the full-scale siphon, it would require 3030 minutes for the vertical chamber of Manhole No. 2 to become one-third full of oil, when the water flow rate is 1770 gallons per minute and the oil flow rate is 3.16 gallons per minute (see Table 3). On the other hand, the data for the four-inch model predict it would require about 1830 minutes for Manhole No. 2 of the full-scale siphon to become one-third full of oil. Under similar conditions, these initial tests indicate that although Froude scaling is not precisely correct, the order of magnitude of the filling times is predicted within a factor of two.

The excessive pooling of oil upstream of the first manhole in the four-inch model, as previously mentioned, caused oil to enter the lower section of the siphon sooner than if the oil pool were not restricted at the upstream end. Once the pooled oil reached the upstream limit, the continued addition of oil caused the accumulated layer of surface oil to increase in depth more rapidly than it would if allowed to increase in area upstream. Thus, for a given water flow rate, it appears that the thickness of the oil pool accumulated at Manhole No. 1 dictates when oil will begin entering the lower siphon section. For an

unrestricted four-inch system, which would have allowed the oil pool to extend farther upstream, it is likely that it would have required up to twice as long for the oil layer at Manhole No. 1 to reach the thickness at which oil began to enter the lower siphon section. In this case, Froude scaling would predict a time for oil filling of Manhole No. 2 of the full-scale system (to one-third its capacity) almost identical with the time predicted on the basis of the two-inch model run.

In general, it was observed that as the thickness of the layer of pooled oil increases, the flowing water stream beneath the oil layer decreases in thickness. Since the water flow is maintained at a constant rate, the stream velocity in the region of the pooled oil increases. The interface between the oil and water slopes downward to the point where it enters the first 45° (downward) bend. As more oil accumulates in the pool, the oil-water interface is carried farther down into the 45° sloping section. Meanwhile, globules of oil tear away from the interface and float upward to join the pooled oil. Eventually when sufficient oil has accumulated upstream, oil begins to flow into the lower horizontal section of the siphon and into Manhole No. 2.

This initial series of tests therefore suggests the appropriateness of Froude scaling. In addition, it demonstrates that inverted siphon configurations are virtually 100% effective for trapping surface oils, a result in agreement with observations made on the full-scale siphon at Memorial Drive.

In order to reduce the running time for the model tests and eliminate the difficulty encountered on the four-inch model with the restriction on the upstream pooling of oil, model test runs were made under Froude scaling conditions at higher water flow and oil flow rates than were used in the initial model tests. The oil and water flow data for the higher flow tests are presented in Table 4. The model flow rates correspond to within approximately three percent to full-scale siphon flows of 5500 gal/min for water and 50 gal/min for oil. The full-scale water flow rate is equivalent to an average daily flow of nearly eight million gallons, which represents a high flow condition for normal sewer operation but which is still much less than the 20 million gallon per day peak flow encountered during storm periods. The 50 gal/min oil flow is representative of a rather large discharge into the sewer as might occur during an accidental or surreptitious spill.

Table 4

MODEL FLOW RATES FOR HIGHER FLOW FROUDE TESTS

	1/24 SCALE MODEL	1/12 SCALE MODEL	FULL SCALE SIPHON
Q_w, WATER	2.00 GAL/MIN	10.65 GAL/MIN	~ 5500 GAL/MIN
Q_o, OIL	0.0173 GAL/MIN	0.100 GAL/MIN	~ 50 GAL/MIN

For the tests on the two-inch and four-inch models, the depths of oil at Manhole Nos. 1, 2 and 3 were recorded at one-minute intervals as the tests progressed. Using the Froude scaling factors presented in Table 2, the oil depth readings and the associated times were converted to oil depths and times for the full-scale siphon. The results are plotted in Figure 18. There is generally good agreement between the two-inch model results and the four-inch model results, particularly with respect to the filling of Manhole No. 2. The four-inch model indicates slightly earlier filling than the two-inch model would predict. Note that the tests for either model show that only traces of oil enter Manhole No. 3 before Manhole No. 2 is completely filled. Again, this is in agreement with the measurements made on the full-scale siphon which show that almost 100% of the surface oil entering the siphon section is trapped in the first vertical standpipe encountered.

The same test data are plotted in a different form in Figures 19 and 20. Figure 19 is a plot of the ratio of Q'_o, the rate of oil accumulation in Manhole No. 2, to Q_w, the water flow rate, as a function of scaled time for the two-inch and four-inch Froude model runs. A similar plot is presented in Figure 20 for the oil accumulation in Manhole No. 3. The agreement for Manhole No. 2 is excellent. In the case of Manhole No. 3, the four-inch model results predict that this manhole begins to fill with oil about 30 minutes earlier than the two-inch model predicts it should. Nevertheless, both models agree in their predictions in the "order of magnitude" sense most useful for engineering designs.

The sequence of photographs shown in Figure 21 illustrates the oil trapping characteristics of the inverted siphon configuration. The top photograph was taken just after Manhole No. 2 began to accumulate oil. Oil globules rising in the vertical chamber of the manhole are clearly evident. Notice that only slight traces of oil are visible downstream of this manhole. The center photograph, taken after the top photograph, shows Manhole No. 2 approximately half full of oil. The bottom photograph shows Manhole No. 2 completely filled and Manhole No. 3 approximately three-fourths full. In this entire sequence, the quantities of oil carried out of the siphon into the discharge stream were immeasurably small.

In another model test series, the water and oil flow rates were adjusted on the basis of Reynolds scaling. The appropriate Reynolds scaling factors are presented in Table 5. Comparison between Table 5 and Table 2 shows that for a given full-scale flow, Reynolds scaling requires much larger model flows than does Froude scaling. It is particularly interesting to note that the velocity required for Reynolds scaling is actually greater than the velocity of the full-scale system. Because of the high model flows required for Reynolds scaling, the simulation of full-scale flows was limited to about 126 gallons per minute (or about 180,000 gallons per day) which corresponds to a flow rate of 10.65 gallons per minute for the four-inch model. The water flow rate for the four-inch model was the same as that used in the Froude

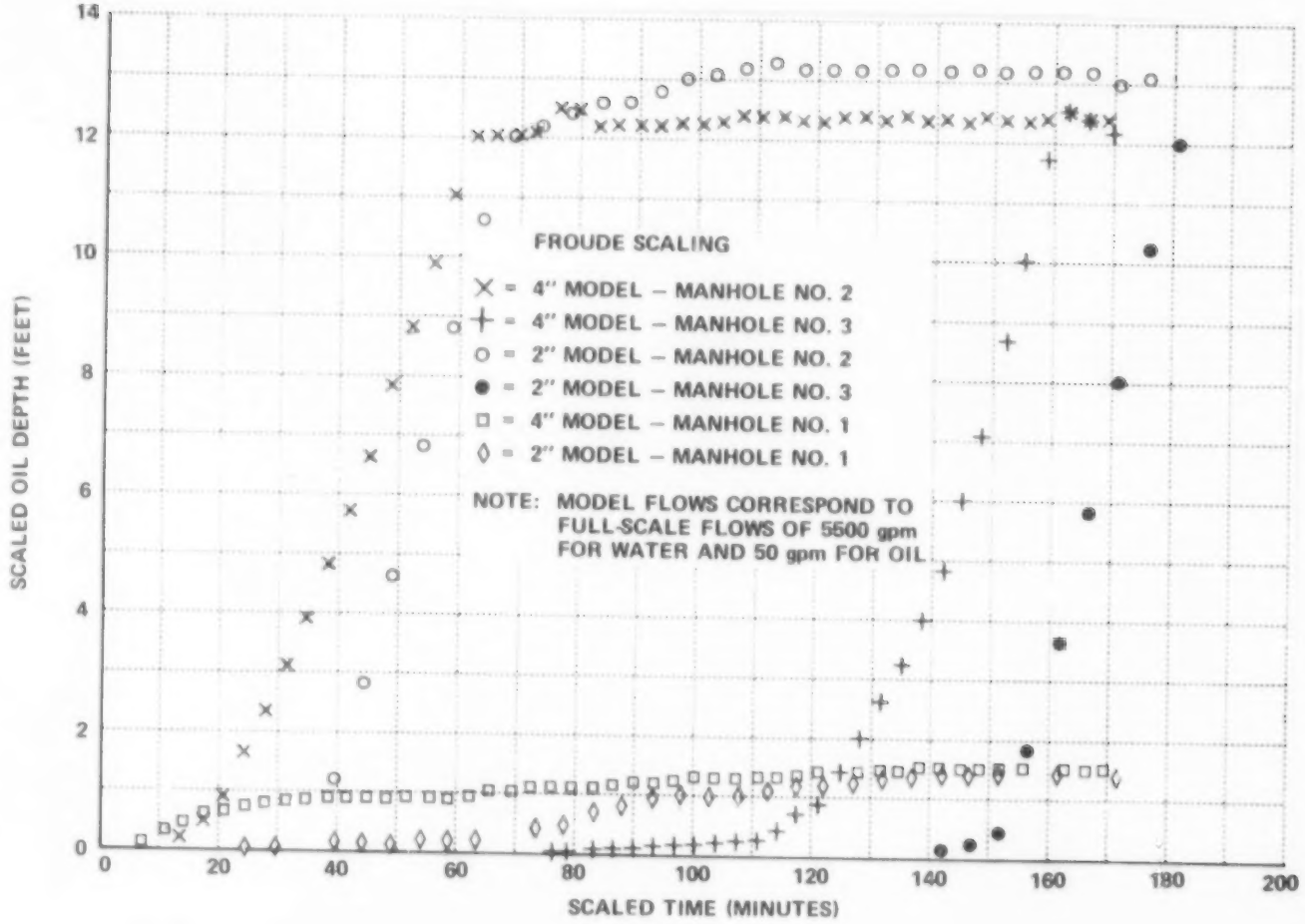


Figure 18 PREDICTED OIL ACCUMLATIONS IN FULL-SCALE INVERTED SIPHON BASED ON FROUDE MODEL TEST

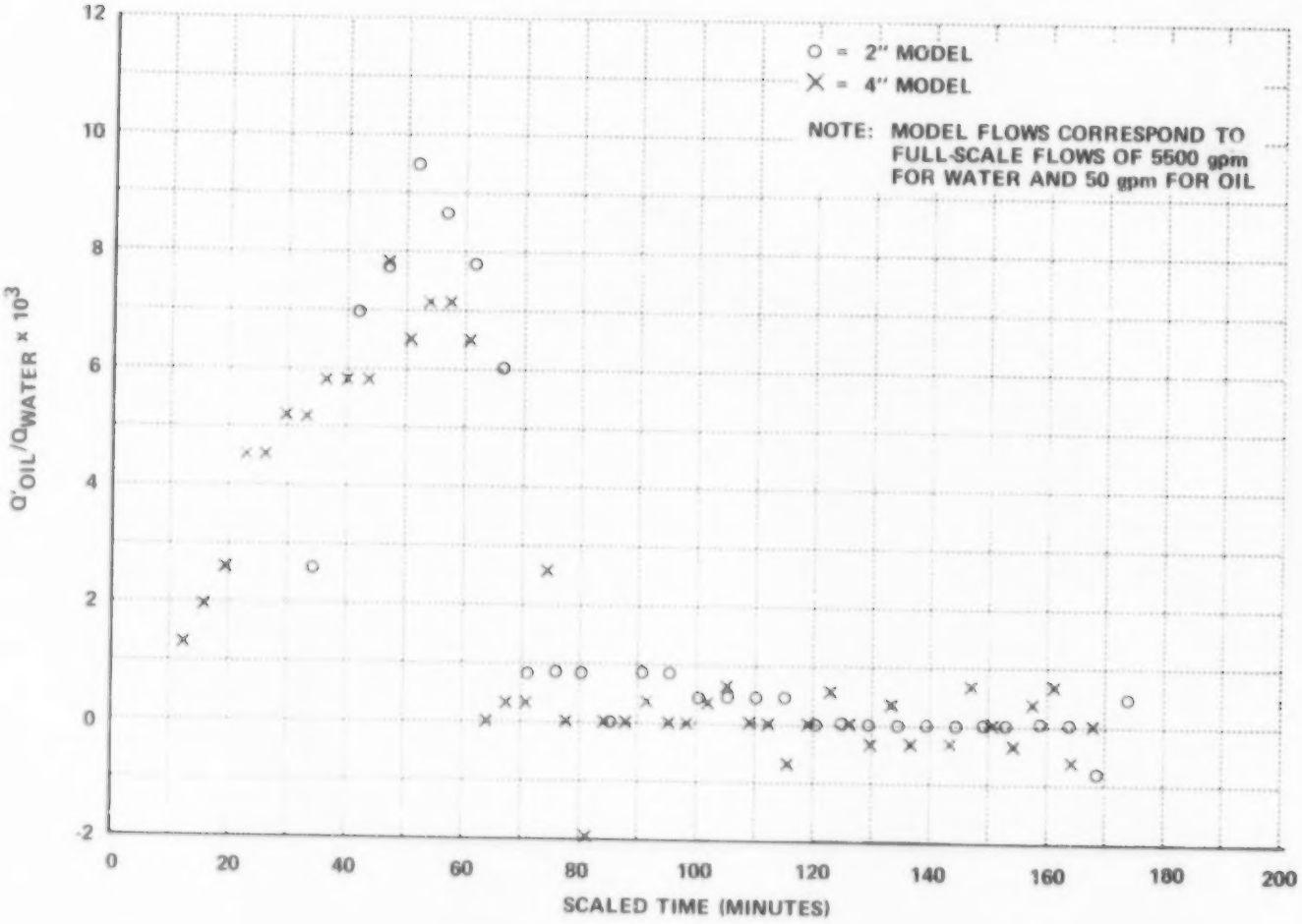


Figure 19 RATE OF OIL ACCUMULATION IN MANHOLE NO. 2 FOR FROUDE MODEL TEST

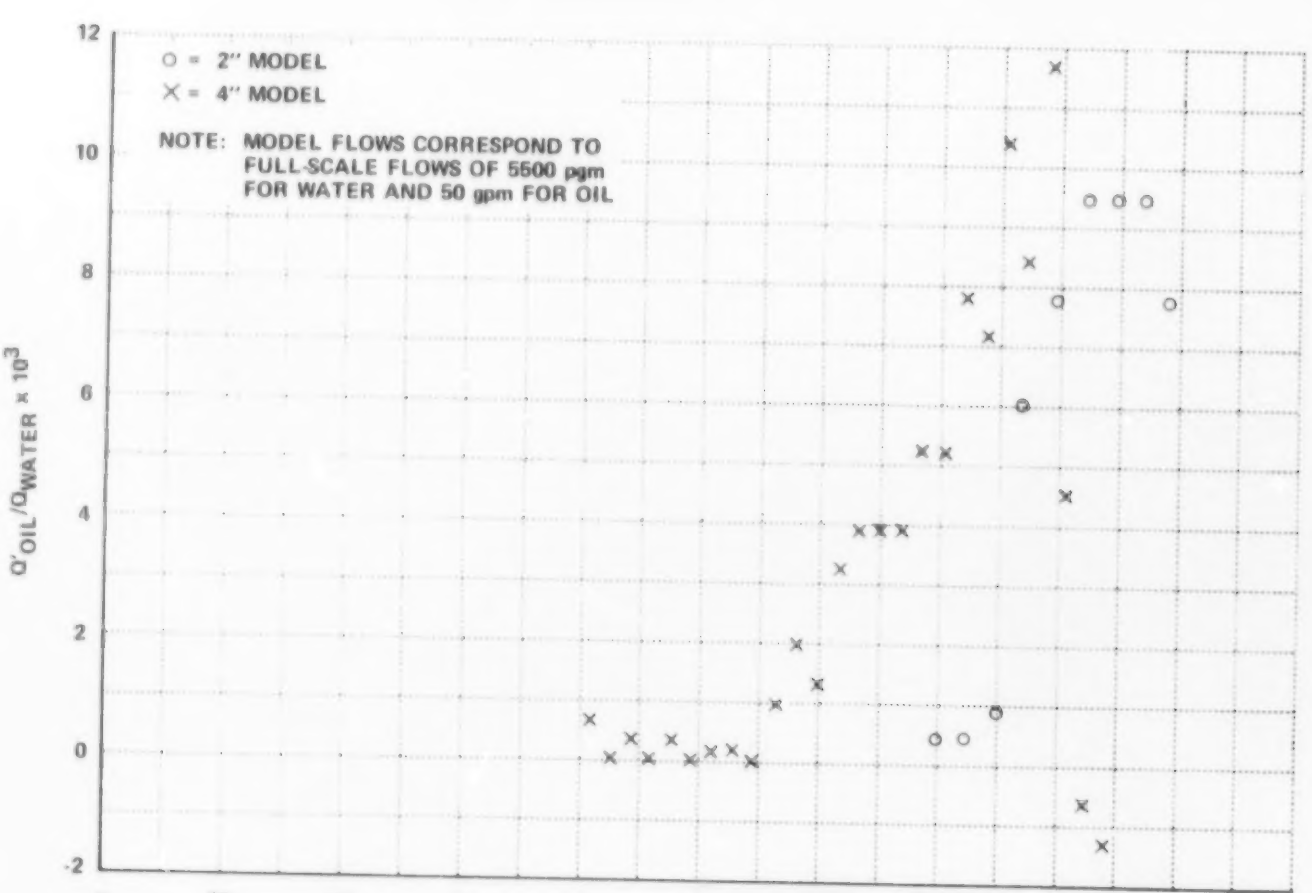


Figure 20 RATE OF OIL ACCUMULATION IN MANHOLE NO. 3 FOR FROUDE MODEL TEST

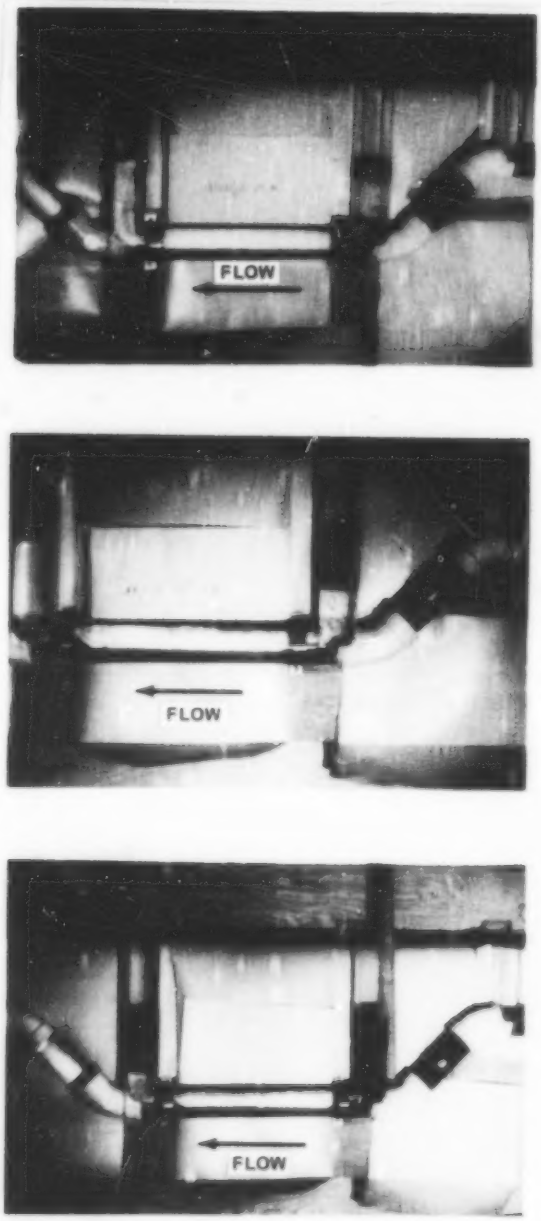


Figure 21 SEQUENCE OF PHOTOGRAPHS SHOWING OIL TRAPPING CHARACTERISTICS OF TWO-INCH INVERTED SIPHON MODEL

Table 5

REYNOLDS SCALING FACTORS
FOR INVERTED SIPHON MODELS

	FULL-SCALE SIPHON (48")	1/24 SCALE MODEL (2")	1/12 SCALE MODEL (4")
CHARACTERISTIC LENGTH, L	1	1/24	1/12
CHARACTERISTIC TIME, t	1	0.001736	0.006944
VELOCITY, v	1	24	12
FLOW RATE, Q	1	1/24	1/12

tests and is about the upper limit for the water supply system used in the model tests. The flow rates used in the Reynolds tests and the corresponding full-scale flows are presented in Table 6.

Table 6

FLOW RATES FOR
REYNOLDS SCALING TESTS

	1/24 SCALE MODEL	1/12 SCALE MODEL	FULL SCALE SIPHON
Q_w, WATER	5.25 GAL/MIN	10.65 GAL/MIN	126 GAL/MIN
Q_o, OIL	0.050 GAL/MIN	0.100 GAL/MIN	1.2 GAL/MIN

Throughout the model runs, the accumulations of oil in Manholes Nos. 2 and 3 were recorded as a function of time. Using the Reynolds scaling factors given in Table 5, oil depths and times corresponding to the full-scale siphon were computed. The results are plotted in Figure 22. Figures 23 and 24 show the ratios of the oil accumulation rates to the water flow rates for Manholes No. 2 and No. 3 respectively. While the two-inch and four-inch model results are in close agreement with respect to oil accumulation in Manhole No. 2, there is considerable disparity shown with respect to oil accumulation in Manhole No. 3. It is particularly significant to note that for the two-inch model, oil begins to accumulate in Manhole No. 3 before Manhole No. 2 is even three-fourths full. Considering that the scaled flows in the models correspond to a full-scale flow of only 126 gallons per minute, it is

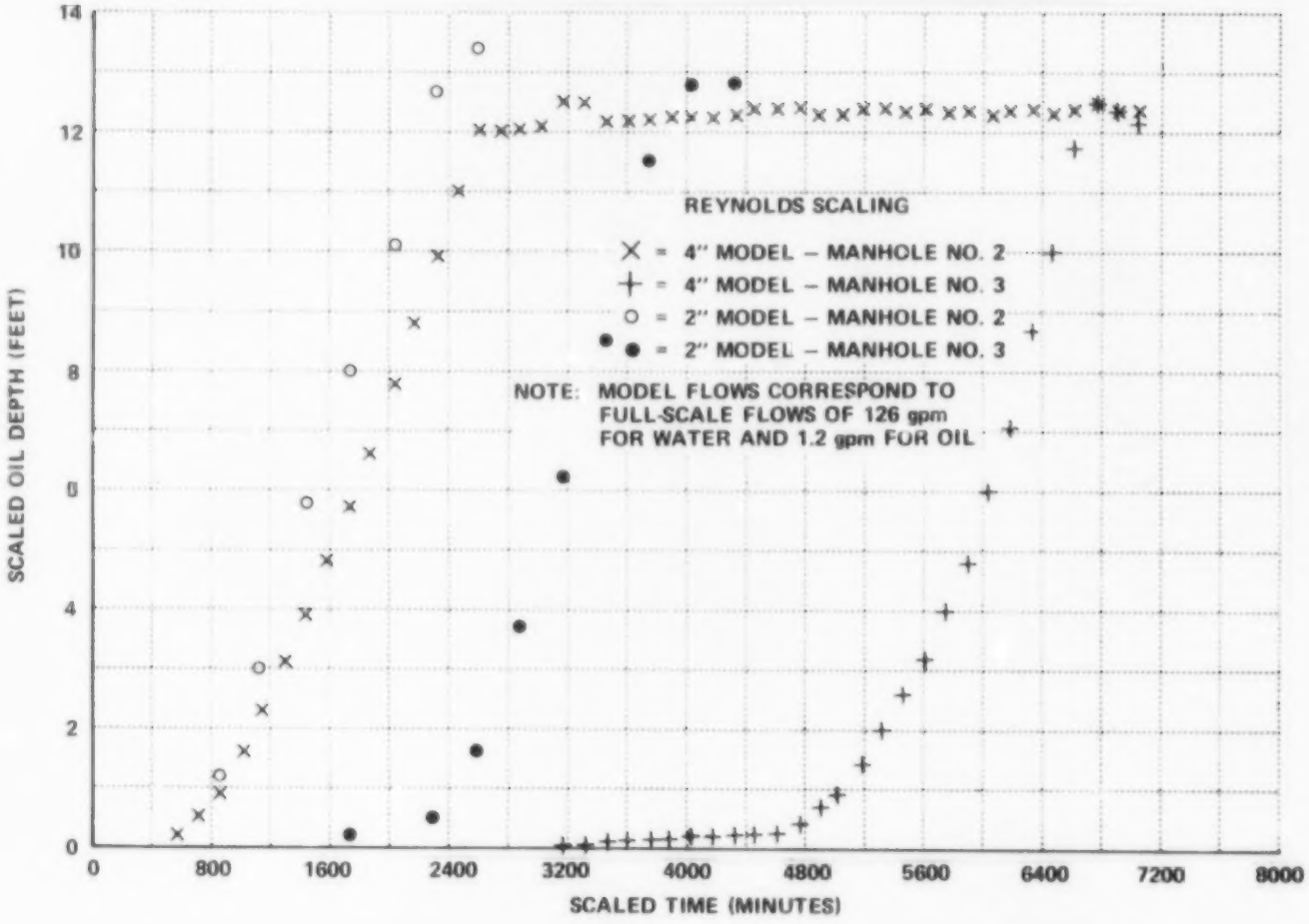


Figure 22 PREDICTED OIL ACCUMULATIONS IN FULL-SCALE INVERTED SIPHON BASED ON REYNOLDS MODEL TEST

highly unlikely (recalling the observed behavior of the full-scale model for even greater flow) that oil could flow past Manhole No. 2 without being trapped. Indeed, the four-inch model results, for which the flow velocity is lower than that of the two-inch model, show that Manhole No. 3 does not begin to fill until after Manhole No. 2 is completely filled. For scaling of higher flows in the full-scale system, it is expected that the four-inch model would also show accumulations in Manhole No. 3 before Manhole No. 2 filled completely. On the basis of the Reynolds scaling tests, it is concluded that Reynolds scaling does not appropriately predict the oil trapping characteristics of inverted siphons. The results obtained are not unexpected, since Reynolds scaling does not take into account gravity forces which come into play to separate the oil and water. Furthermore, for smaller-scale models, the velocity increased under Reynolds scaling. The higher stream velocity and the smaller width of the vertical manhole chambers suggests that for small scales, a scale size will be reached for which some oil will necessarily by-pass the manhole chambers without being trapped.

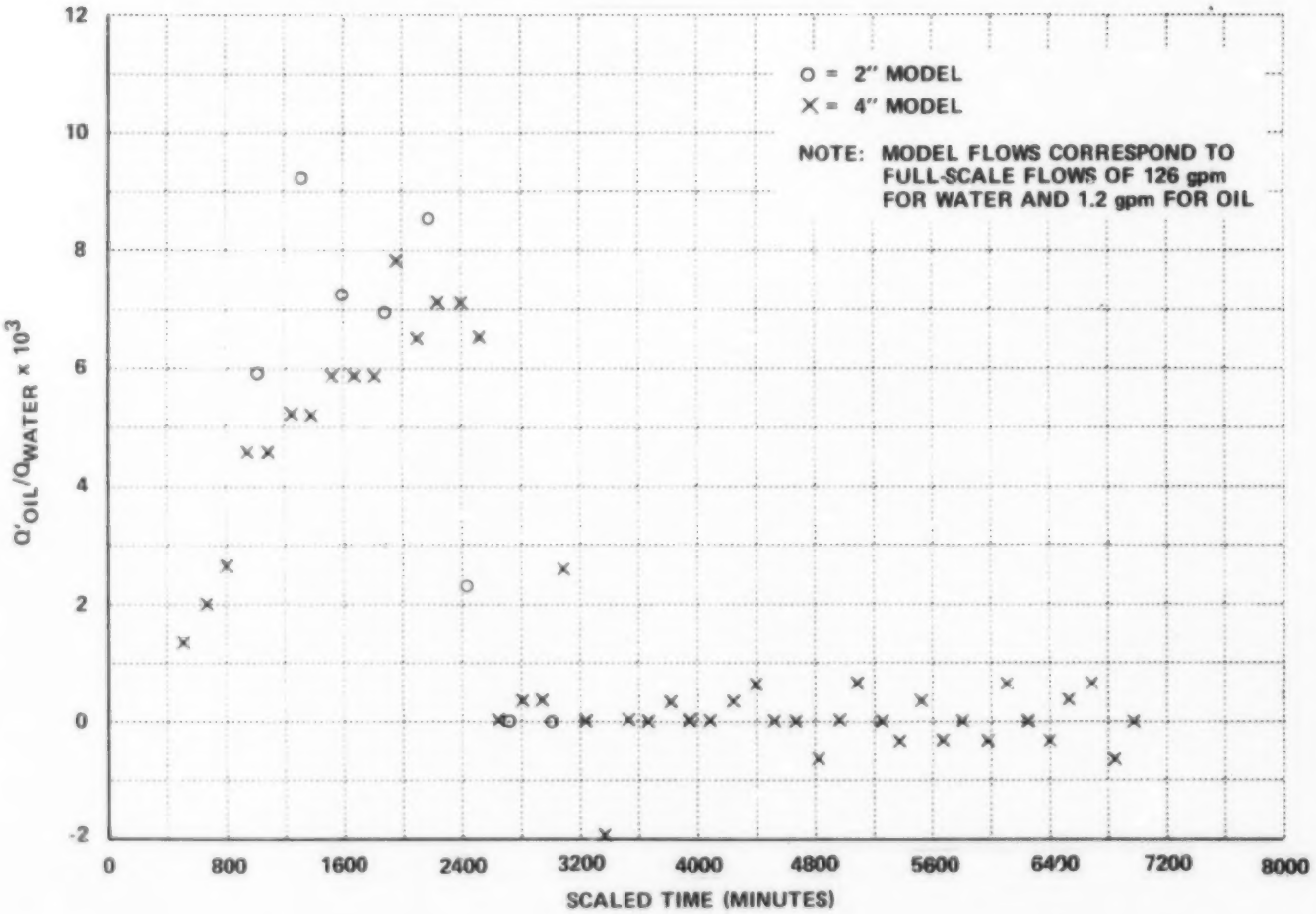


Figure 23 RATE OF OIL ACCUMULATION IN MANHOLE NO. 2 FOR REYNOLDS MODEL TEST

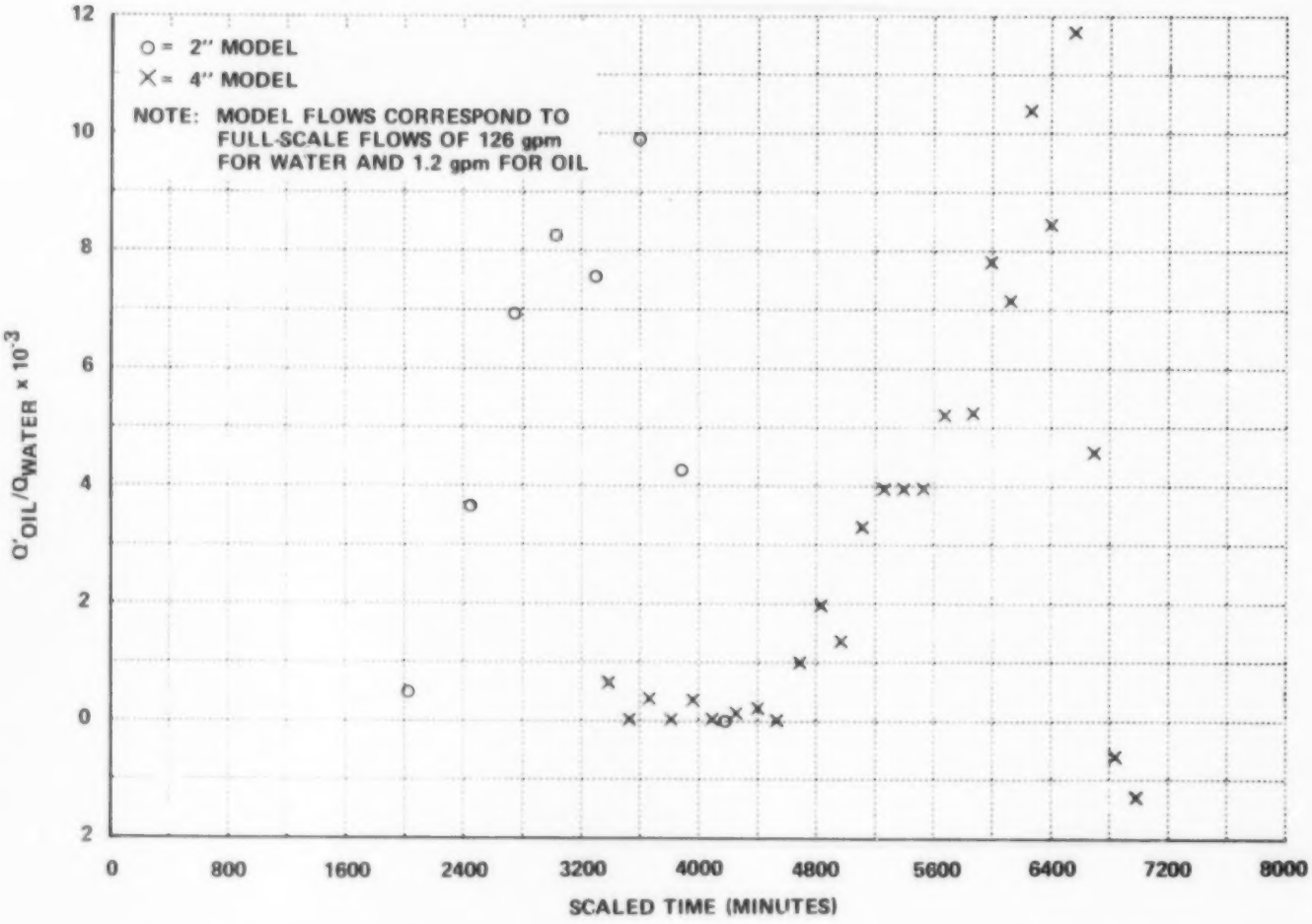


Figure 24 RATE OF OIL ACCUMULATION IN MANHOLE NO. 3 FOR REYNOLDS MODEL TEST

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